V. *On the Present Distribution and Origin of the Calcareous Concretions in Coal Seams, known as "Coal Balls."*

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[Plates 17—19.]

Contents.

Section I.

Introductory.

To botanists and geologists alike coal and the beds associated with it afford a rich field for investigation. Geologists have long been particularly fascinated by the theories which attempt to account for the mode of origin of the coal, and as a result a vast literature has been built up in support of the various views of the

authors who have dealt with the problem. Nevertheless, for our purpose, it is enough merely to name the two main theories which now hold the field, as the "growth *in situ*" and the "drifted" origin for the plants which compose the coal. It will, perhaps, be well to express clearly at the beginning of this paper that we do not propose to enter into a critical discussion of the views of other writers on the subject, except where they have a very direct bearing on our own investigation. It will be found that the results of our work have a certain bearing on the wider subject of the origin of coal in general, but in this paper we wish to confine ourselves to the consideration of questions suggested by the "coal balls" in particular. The conclusions drawn from the special aspect of the case are not applicable to all seams of coal, though they illustrate fully the history of certain seams.

The calcareous masses which occur actually embedded in the coal of some districts have proved of vital importance to students of botanical anatomy and phylogeny, because they contain plant tissues so perfectly petrified that the complete structure of the plants can be discovered by microscopic investigation. Yet although these calcareous masses or "coal balls" have been the source of so much valuable information, little is to be found in the literature, and one gathers also that but little is actually known to scientists about their mode of occurrence and the many interesting phenomena presented by their relation to the beds in which they are found. We have endeavoured to collect and preserve information about these structures, which are being daily destroyed, information which may prove of service to both botanists and geologists.

It will be recognised that the problem of the origin of the calcareous masses in the coal is one distinct from that of the origin of the coal seams themselves. It is with the former problem alone that we are concerned at present, but its solution throws so much light on the latter that to a certain extent the two will be considered together when we present our conclusions.

On first undertaking the field work and the necessary visits to many different localities we found that there was extremely little help or direction to be gathered from the literature. The older generation of palæobotanists who had collected their own material and were well acquainted with the positions in which it was to be found had left very few *field* records and instructions for the use of those who were to follow them. The officers of His Majesty's Survey, to whom we have to return thanks for help given on several occasions, were not in a position to give any information about the occurrence of these structures, which had lain somewhat outside the boundaries of their recent work. Of all the writers BINNEY gives more help than any other, and to his work constant reference will be made, though the condition of stratigraphy at the time he wrote was such that many of his details regarding the correlation of beds have now to be revised in the light of more recent work. It is very unfortunate that he did not leave behind him some record of his valuable field knowledge of the localities and conditions in which the plant-

containing nodules are found. The same applies to the others who worked at this time, his contemporaries and students. WILLIAMSON, whose epoch-making work on the structure of the plants is so well known, recounts but little which bears directly on the problems encountered in the field. WILD leaves practically no published record, and his manuscript notes yield but little of the desired information which he could undoubtedly have supplied. Of the circle of field workers and collectors WILLIAMSON gathered round him but few remain. We have spoken with Mr. EARNSHAW, whose name is frequently mentioned by WILLIAMSON as supplying fossils and information, but his health no longer allows him to contribute anything further to the subject he has studied so long.

There remains, however, Professor BOYD DAWKINS, who connects the older school with those actively working to-day, and to him we owe much helpful counsel. We both gratefully acknowledge that the guidance of Mr. JAMES LOMAX, whose exceptional experience in the mines of Lancashire has placed him in possession of unique local knowledge of the "coal balls" and their surroundings, was of the greatest possible value to us at the commencement of our work. In the original scheme of things this paper was to have been written jointly with him, but as it was then planned, it would have treated of a rather different and more local aspect of the subject. As the work progressed we felt our views diverging more and more widely, and as finally we two made further observations about which Mr. LOMAX disagreed with us, and which lay entirely out of the realm of the original theme, it seemed better to submit separate accounts of our work. We acknowledge, however, with the greatest pleasure and gratitude, the many instances of his valuable collaboration on expeditions, particularly to Shore.

Historical.

More detailed references will be given to papers of importance in the course of the work. For the present it suffices to give in outline the chief views which have been held regarding the origin, and statements made as to the occurrence of the coal balls found in the somewhat scattered literature.

Although the structure of certain fossil plants had been described at a much earlier date, HOOKER and BINNEY ('54) were the first to give any clear account of the actual calcareous masses in the coal, now so well known to palæobotanists. BINNEY, as a student of local geology, had had a long preparation for this work, and in his earlier papers describes the geological characters of the beds in which he afterwards recognised the coal balls. So long ago as 1836 LOONEY remarked on the coal seam and the marine shells associated with it, which has since become the subject of special research. In the preface to ELIAS HALL'S map (see HALL ('36)) he writes: "Under this rock (the Gorse Hall Rock) there is a small one-foot coal, and under it a small two-feet, known by the name of the Mountain Mine, between which two coals the only marine shells of our coal formation are found." He then

gives a list of the marine shells, which are those in connection with which the plant-containing calcareous masses are always found. In 1840, BINNEY ('40) described the various Lancashire coal seams in association with which marine shells are to be found, describing what he considered as several horizons in the Lower Coal Measure series, and giving detailed lists of the beds and fossils contained in them. This previous knowledge of the geological features of the beds must have influenced him considerably when he came to deal with the "coal balls," as we see in his joint paper with HOOKER, where the authors state (p. 150): "The immediate cause of the calcification [of the plants] was no doubt due to the abundance of fossil shells in the shales immediately overlying the coal and nodules."

In 1868 he published his most important work on fossil plants, and prefaced the purely botanical portions of the paper with a short account of the "geological position of the specimens." From the tabulated list given in this paper (BINNEY ('68)) it is clear that he considered that the "bullions" containing petrified plant remains occur in several geological horizons. One can no longer accept these facts as proof of the distribution of the structures, because stratigraphy has advanced since BINNEY's time, and the difficult work of correlating the various coal seams is now much more complete than it was then. Recent workers have treated the occurrence of the calcareous bullions in the coal and the marine shells in the roof as typical of a single horizon, and have, therefore, correlated all the seams in which they occur in both Lancashire and Yorkshire as forming one definite geological horizon.

The work of correlating the large number of small coal seams which appear in the Lower Coal Measures of northern England is a very difficult one, and is not yet completed, while the confusion is still considerably increased by the very numerous local names, some of which are used in different senses in the different localities. The most concise recent account of the coal seams of this age is given by BOLTON ('98), who tabulates the various beds and collects the local names of each. In this paper he restricts the "Bullion Seam," or "Upper Foot Mine" as it is sometimes called, to a single horizon. In a later paper, BOLTON (:04, p. 408) says of this horizon: "Speaking generally, it can be traced with the greatest ease over the whole of the Lower Coal Measure area in Lancashire and onwards into Yorkshire, where, as the Halifax Hard Bed, it is as readily recognisable as elsewhere." . . . "Wherever it occurs it seams to yield the 'baum pots' with their loads of animal remains and the even more celebrated 'bullion balls,' always rich in well-preserved plant tissues."*

The above quotations are sufficient to make clear the view which is at present generally accepted by miners and those whose work comes in touch with the mines

* It should, perhaps, be stated that the calcareous masses in the coal are known by several names, viz., "coal balls," "seam nodules," "bullions," or "plant bullions"; while at the same time the Goniatites and other marine shells in the roof are constantly found in large concretions known variously as "roof nodules," "baum pots," "baum posts," "bullions," and "Goniatite nodules"; the latter frequently contain *isolated* plants among the marine shells, but they are always found in the roof and not in the coal itself.

of the district, as we see once more in the statement made by LOMAX (: 02) : "As we all know, there is only one seam of coal in which we find these nodular concretions."

The concretionary nature of the coal balls was recognised by the earliest workers, and the analysis given by HOOKER and BINNEY (see p. 194) has constantly been quoted to show that they are mainly composed of carbonate of lime. Very few facts have been brought forward in order to show how they were formed in the coal, though several suggestions have been made. The chemistry of the subject was gone into for the first time by STOCKS (: 02) in a paper before the Geological Society, in which he gives fresh analyses both of the coal balls themselves, and of detached pieces of fossilised wood taken from them. He then gives a detailed account of experiments and observations on the precipitation of calcium carbonate under varying conditions, the action of salts of lime and iron on wood, and of bacteria on mineral solutions, concluding that bacteria played a large part in the anaërobic decay, and that the minerals were first deposited in the bacterial jelly. In our Section IV the subject will be treated of in detail, so that further reference to STOCKS' work will not be given here.

One of the most important points in connection with the calcareous nodules in the coal is to determine their relation to the coal (itself), in which they are found embedded. HOOKER and BINNEY ('54) state that "A section of these nodules shows a confused mass of decayed and apparently decaying vegetable remains; they present no appearance of these remains having been brought together by any mechanical agency; they appear to be associated together just as they fell from the plants that produced them . . . . ." and that therefore the nodules represent samples of the plants forming the seam. This is the view generally accepted by palæobotanists. It must be noted, however, that neither HOOKER and BINNEY nor their followers have *proved* this to be the truth, no definite facts have been brought together and marshalled so as to show that the plant-containing masses are not drift material brought in from some other source. On the other hand LOMAX (: 02) states definitely that his experience in the mines leads him to believe that "the various portions of plants have been carried to their present position after being broken in fragments, and before petrifaction, or they have been carried from a parent bed after petrifaction," thus bringing forward an opposing view, which, if proved, would make it clear that the "coal balls" do not contain representative plants of the coal in which they are found, but have been derived from another locality, possibly even from an earlier epoch. It is of prime importance to determine which of these two views is correct, for upon our interpretation of the facts depend all the theoretical considerations and the conclusions which are to be drawn from the structures found in the "coal balls."

In this present paper we bring forward a series of facts which appear to prove conclusively that the coal balls do actually represent the flora of the coal in which

they are found, thus supporting the conclusions reached with more scanty evidence by HOOKER and BINNEY.

The subject of the coal balls and their structure was discussed at the York Meeting of the British Association for the Advancement of Science, 1906, when Professor WEISS (: 06) contributed a paper dealing with the past work on the subject, which was followed by one (STOPES, : 06) giving an account of the work which was being done at the time. The facts then stated, and the conclusions drawn being similar to, but less complete than those presented in this paper, no reference to the York communication is needed here.

Scope of Present Paper.

In the course of the present paper we present the work done during the last three years, largely in the field and in mines where the "coal balls" occur, but also in the laboratory. The facts here described illustrate:—The internal structure of the "coal balls," and their relation to the coal in which they occur, their size and position in the seams, their chemical composition, and their relation to the "roof nodules" above them. Many of these facts give support to the view of the origin *in situ* of the calcareous "coal balls."* We also present facts in support of the statement that they occur in *more than one* geological horizon; experiments and deductions showing the importance of the peaty acids and sea water in the preservation and fossilisation of the plant tissues in the coal balls, and the possible chemical reactions which took place during the process of mineralisation. Further, a comparison is made between the type of flora found in the roof shales and nodules and that in the seam, and their respective origins.

SECTION II.

Details of the Occurrence of the "Coal Balls" in the Seams.

Delicacy of the Tissues preserved.—Before examining the masses as actually seen in the mine itself, it may be well to remind the reader of the extreme delicacy of some of the tissues seen in the petrified masses. As is well known, the "coal balls" can be cut into sections and ground down sufficiently thin to allow of microscopic examination, and they then reveal portions of various plants, with their tissues more or less perfectly preserved. It has been remarked already by many authorities, WILLIAMSON, SOLMS LAUBACH, SCOTT, SEWARD, and others that the most delicate tissues of the plants, such as phloem, endodermis, aerenchyme, etc., are constantly preserved with great perfection, and have remained entirely uncrushed in the "coal

* The *in situ* theory of the origin of the calcareous coal balls does not *necessarily* mean the *in situ* theory of the coal seam in which they are found. It is used to indicate the view that the calcareous concretions were formed in the coal substance after it was collected in the position in which it is now found, and that the balls themselves have not drifted as such from any other region.

balls." Recent work has revealed still more wonderful cases of delicate preservation, such as early stages of germination in fern spores as described by SCOTT (:04). We illustrate, fig. 1, Plate 17, the growing point of a *Lyginodendron?* root, in which the young dividing tissue is excellently preserved. Such cases as these somewhat increase the difficulty of finding a satisfactory theory of fossilisation, because it is impossible to suppose that such delicate tissues could remain for a very lengthy period undecayed prior to the entry of the fossilising fluid. It is also certain that they could not have been tossed about much before they were preserved, nor could any great weight of tissue have lain above them, for it is found that the bottom layers are very much crushed by the weight of even a few feet of superincumbent peat.

It is necessary, therefore, while examining the structures in the mine, and while considering the facts seen there, to remember the extremely delicate and destructible nature of the tissues preserved in the calcareous coal balls.

Position of "Coal Balls" in the Seam.—The "Upper Foot" or "Bullion" Mine, in which the balls are found abundantly, is one of the smaller mines towards the base of the Lower Coal Measure series. It is a small coal, generally about a foot thick, with a shaly roof, in which the roof nodules with their many goniatites and other marine shells are found. The "coal balls" lie actually in the coal itself, completely surrounded by it, and scattered irregularly throughout its thickness. It is noticeable that they do not occur in lines or bands, as do flints in chalk, or "dirt beds" in ordinary coals, but that they are scattered without any order from bottom to top of the coal (fig. 4, Plate 17, and text-fig. 5, p. 189). The "coal balls" individually are of very varying size and shape, though on the average they are roughly spherical. BINNEY ('68), p. 13, mentions that they vary from 1 inch to 1 foot in diameter, but we have found them to vary within considerably wider limits. In the same paper BINNEY also gives a small diagram showing the larger "coal balls" projecting up through the coal into the roof above, quite irrespective of the bedding planes of the coal. We have always found that even in cases where this appears to be the case, careful examination will show a lamina of coal round the "coal ball," the remainder of the coal being crushed by the weight of the superimposed strata, which could not affect the stony ball itself.

Bending of Laminæ of Coal round the "Coal Balls."—In the mines it is very commonly noticeable that the bedding of the coal is bent round the nodules. This is shown in an entirely diagrammatic form in text-fig. 1, and may be seen in the photograph in fig. 2, Plate 17. This arrangement shows that the "coal balls" must have been in position before the mass of vegetation was crushed into coal.

Signs of "slickensides" between the laminæ of the coal and the surface of the ball are to be observed almost universally, and are an indication that the later movements of the seam found their course in the layers of coal itself, and left the harder concretions uncrushed. In a few cases we have observed "faults" running

through an actual nodule, and either shattering and somewhat crushing it, or breaking it in half and slightly displacing the portions. Instances of this appearance are illustrated in fig. 3, Plate 17, and fig. 9, Plate 18, but they are undoubtedly uncommon, and were not easily found.

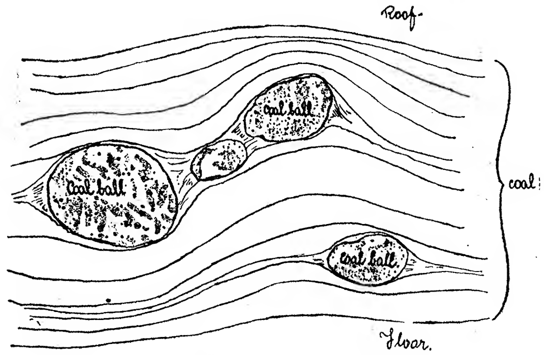


FIG. 1.—Portion of coal seam with "coal balls" to show the bending of the laminæ of the coal round each nodule.

The fact that these larger calcareous nodules in the seam were left uncompressed, while the coal around them underwent considerable reduction in vertical thickness, is particularly well illustrated in the case of an exceptionally large mass which was found in the mine at Shore.

Enormous "Coal Ball."—This single mass was estimated from measurements to weigh at least 2 tons, and was several feet in diameter. It is seen *in situ* in fig. 4, Plate 17, and a small part of it on a larger scale is depicted in fig. 9, Plate 18. Where it is seen in the coal seam itself, it shows the great thickness of the mass in comparison with the coal seam in which it lies, and which thins out to the normal foot on either side. This enormous mass has entirely replaced the coal seam where it occurs, leaving but a film of coal at the top and bottom, and as it is composed of solid uncrushed carbonates of lime, its original size is retained, while the coal has been compressed on either side. The large mass may practically represent the thickness of the original seam before the plants had been compressed to form coal. A similar thickening of the seam is to be observed on a smaller scale wherever large numbers of the ordinary small nodules occur thickly together, as the compressibility of the seam as a whole is thus reduced.*

The enormous nodule in the seam, mentioned above, merits special description, on account of its somewhat unusual structure and very exceptional size. Single coal balls nearly 2 feet in diameter have been found, and from 1 to $1\frac{1}{2}$ feet they are common in the Old Meadows Pit, at Bacup, and elsewhere, but these were the

* Our friend, Mr. J. BARNES, informs us that in his experiments on the artificial production of coal, about 5 feet of peat are compressed to form 1 foot of coal. This corresponds fairly closely with the indications from the huge coal ball, which is nearly 4 feet thick while the coal on either side is slightly under 1 foot.

largest known until the Shore mass was found. It is of very considerable theoretical importance, for so large a mass cannot have been transported in the way the small "coal balls" might be considered to have reached their present position. A portion of it, blasted off from the main mass,* after washing with acid, revealed clearly that the whole mass is penetrated by plant tissues. A small portion of the block enlarged (fig. 9, Plate 18) illustrates the concretionary centres which are to be seen in it, a number of which have been joined together by intervening deposit of carbonates of lime and magnesia, which binds the whole together as one solid mass. These concretionary centres show up with particular clearness in the large specimen, and are also on a larger size than those to be seen in the average "coal ball." As well as the petrified plant tissues which penetrate the carbonate mass, streaks of coaly matter run irregularly through it. This shows with additional clearness that the mineralisation forming the large block must have started in a number of different centres in the plant mass, and that the regions of petrifaction met and fused, but that here and there the coal film was left between the individual nodules, a film which, in the case of the average nodule, is represented by a considerable thickness of coal between it and its neighbour. There are also signs of faulting and slight later displacement in the main mass, which can be seen to have taken place after the concretions had been formed (see fig. 9, Plate 18); these were probably due to later earth movements, or the mere weight of the superincumbent strata. In the case of a mass so large as this, the force would come to bear on it directly, and would not slip off through the softer coal layers, as in the case of the small nodules scattered thinly through the coal.

One of the arguments used by those who hold the view that the nodules in the coal are derived from some source other than that providing the coal itself, is that these nodules or "coal balls" are rounded and very commonly spherical in shape, and that they must have received their rounded form, as pebbles do, as a result of rolling over one another in a current of water. Against this argument may be urged the fact that concretions are typically spherical or approximately spherical in form. We have in the large mass (see figs. 4 and 9) very clear evidence that the carbonates accumulated as concretions, evidence which is widely supported by the structure of the smaller examples (see fig. 13, Plate 19), so that there appears to be no necessity to invoke the pebble-forming action of moving water to account for the rounding of the "coal balls."

When we consider the possibility of streams having ever transported the calcareous coal balls, we find in the 2-ton mass a strong argument against the likelihood of such an occurrence. A solid mass of stone weighing over 2 tons, if it is to be moved by water, necessitates a very much greater transporting power than was probably present in the streams connected with the deposits which gave rise to

* *Cp.* the two halves—now in London and Manchester—of a much bigger part of the mass.

our coal seams. Everything in the physical geology of these deposits makes it unlikely that there were mountain torrents rushing through them, and it would require a mountain torrent to transport a block of stone of 2 tons weight. It has been suggested that the mass might have been brought as separate pebbles and cemented together in the place it now lies; but there is no internal evidence for that, and even were this to be conceded, the process of cementing the block together has certainly taken place *in situ*, and if so, why should not the whole formation have taken place in the same spot? The momentary concession, however, cannot be permanently granted, and we see in the large size of the mass at Shore, as well as in the larger nodules so commonly found, a strong argument in favour of the *in situ* theory of petrifaction.

A type of petrifaction which is found in a mine at the Great Harwood Colliery is a further proof of the above view.

Sheets of Stone corresponding to Coal Balls.—There are several peculiar features in the coal of this mine which will be considered later on (see p. 190), but in other particulars it is a parallel formation to that of the normal "coal balls." In this mine the calcareous masses contain extremely fragmentary plant remains, but they are there in considerable quantity and are petrified in a similar fashion to those in the usual ball. Instead of forming large rounded concretions, however, the stone lies in sheets in the coal, forming thin lenticular patches which may reach the size of large slabs of stone 6 inches or so in thickness and several feet square. These run horizontally between the bedding of the coal itself, in a way which is diagrammatically illustrated in text-fig. 2.

FIG. 2.—Diagram of coal with thin horizontally lying slabs of stone containing plant remains (thickness, 4 feet).

The plant tissue petrified in these slabs is much less well preserved than are the plants in the true coal balls, and it may well be the case that in this bed the plants forming the coal itself may have partially drifted and decomposed before they accumulated in their present position; but there is no possibility that the slabs of stone were formed in any other place than in the coal in which they are now lying, because of the difficulty of conceiving a physical force which could transport, as such, flat blocks of stone, sometimes 10 feet by 3 feet in size and 6 inches thick, and place them horizontally in the coal.

Hence in these slabs of petrified *débris* we see evidence that calcareous matter can be formed in the seam, replacing the coal itself, which evidence acts as a further support of the *in situ* view of the origin of the true "coal balls."

Dolomite in the Wirral Colliery.—Another interesting and important case, which appears to be a parallel to the Lower Coal Measure "coal balls," has been described from the Middle Coal Measures by STRAHAN (: 01).

At the time his paper was written STRAHAN had not recognised the connection existing between this phenomenon and the "coal balls" of the Upper Foot Mine; in fact, he states that the case is "unique in the fact that the place of the coal is taken by dolomite, and that the change takes place within the distance of a few yards."* Unfortunately the seam is now quite worked through, and is lost for ever in the back workings of the mine, but owing to the kindness of Mr. PLATT, the Manager, who had supplied Mr. STRAHAN with information, and who volunteered all the additional help he could give, specimens were obtained. With these specimens, the facts Mr. PLATT could affirm, and the use of the original slides and hand specimens kindly lent to us by the Geological Survey, it became clear that in the Wirral mine a process had taken place which is almost identical in essence with that which formed the "coal balls," but that owing to local conditions it appears superficially very different.

According to the manager of the mine, the first unusual character observed in the coal was the appearance of a number of "pea-" or "shot-" like balls of stone. These we figure in fig. 8, Plate 18, and it will be seen that they are concretions, smaller than, but otherwise very similar to, those found in the mines containing "coal balls." They contained plant tissue more or less perfectly petrified, as is to be seen in fig. 5, Plate 12, of Mr. STRAHAN's paper, though the tissue is not so well preserved as is general in the larger bullions, and they may be directly compared with the very small type of coal ball which, whilst not so common as the larger type, can yet be found (illustrated in fig. 7, Plate 18) in the Lower Coal Measures.

The number of these stone pellets increased till bands of stone were formed, replacing the coal, at first in thin streaks, but in rapidly increasing number and size until practically no coal was left, and what appeared to be a very uniform and coarsely granulated rock took its place. Specimens of this rock which we had cut (fig. 15, Plate 19), as well as that shown in Mr. STRAHAN's paper, fig. 1, Plate 12, show innumerable centres of concretionary action. In the rock of this type very little or no plant tissue is recognisable, but in some parts thin streaks of coaly matter are seen to run between the concretions.

The theoretical conclusion come to by STRAHAN from the facts he described is that the dolomite "tufa" beds replacing the coal must have been deposited in water in which the coal seam was also being deposited, but that locally the water must have been so free from clastic material that even plant *débris* was of rare occurrence; thus the dolomite was deposited in a pure condition, and free from plant remains. His argument, however, does not seem to us conclusive when one considers the difficulty of imagining such locally pure regions in a place otherwise filled by plant

* It may be noted that here dolomite replaces the coal, while the coal balls are spoken of as calcareous. In reference to our Section IV it will be seen that the analyses we give there show that the coal balls are frequently formed very largely of dolomite.

débris, which, in Mr. STRAHAN's own words, "are finely divided, and even after mineralization take long to settle; before mineralization they must have been in a condition to travel with the smallest movement of the water" (p. 302). As Mr. OLDHAM pointed out in the discussion, it is "difficult to understand how such easily transported *débris* as vegetable matter could so abruptly cease and give way to a mineral deposit." Mr. STRAHAN's argument from the lack of plant remains in the dolomite fails when one compares its chemical composition with that of a coal ball. In the three analyses of the dolomite given by STRAHAN the percentage of "coaly matter" stands at 4·09, 2·99, and 17·80 per cent. respectively, which gives an average considerably higher than the percentage of carbonaceous matter found in the "coal balls"; to take a few examples at random, from our Table I, p. 193, we get 1·8, 2·28, 4, and 2·7 per cent. of carbonaceous matter.

Now in the case of the latter analyses (the true "coal balls") we know that the mineral matter is entirely permeated by plant remains because the tissues are still there, so well preserved that every cell may be seen and there can be no doubt that the mineral matter was deposited round the plant tissue. An explanation of the small amount of carbonaceous matter found in such coal balls is given in Section IV, p. 200: for the moment it suffices to point out that in these cases where the mineral is deposited absolutely in the tissue of the plant, there is *less* carbonaceous matter than is present in the dolomite described by Mr. STRAHAN. For this reason his argument, that the dolomite must have been deposited in water absolutely free from plant *débris*, appears to us invalid. It is true that in the bulk of the dolomite stone, plant tissue is not recognisably preserved, and that at first sight it appears entirely free from such structures except for very decomposed coaly fragments; but such an appearance is no proof whatever that plant structures were not present and decomposed during the formation of the mineral concretions. In fact, a number of cases can be observed illustrating this in an ordinary "coal ball," where the process has taken place on a smaller scale, and in the midst of a stem otherwise preserved so that each cell is recognisable small concretionary masses may be seen with no trace of plant tissue in their purely crystalline structure. In such cases we know that the water in which the mineral was deposited could not have been free from plant *débris*, none the less the mineral appears now to be free from it. We need not follow the argument further: enough has been said to show that there is strong evidence on the side of the view that the Wirral dolomite was deposited amidst plant *débris* at the same time that the coal was being formed. When compared with the "coal ball" formation in the lower seams, it becomes clear that the case is not unique as Mr. STRAHAN supposed, and that in fact it is quite a parallel development to that which formed the coal balls. This case is a useful example to illustrate the great size which may be reached by mineral masses in coal, and affords a further illustration of what we saw in the lower beds, viz., that they may be very much too large to have been transported after their formation. No one could suggest that

a seam of rock 3 feet thick and several hundred yards in extent could have been brought as such and deposited in the coal.

Occurrence of the Nodules in "Pockets."—It was soon remarked that in the mines in which the typical "coal balls" occur they appear in local patches, and that the tendency is for the coal between the areas rich in "coal balls" to be almost free from them. This distribution in "pockets," as the areas rich in coal balls are called, led to the conjecture that each pocket might represent the section of a stream, and that the whole series were sections of a system of streams which had run in winding courses through the delta-like area in which the coal was being deposited. Careful measurements and plans were taken of the workings at Shore, where we had exceptional advantages owing to the kindness of Mr. SUTCLIFFE, and these showed that the "pockets" are not connected with each other, nor do they extend any great distance in a horizontal direction, but are simply local patches of roughly circular form, in which the coal balls are more plentiful than in the rest of the seam. The distribution of these patches is quite irregular, and it appears that their formation must have depended on some trifling local condition. It is often noticeable that where the "coal balls" are most abundant in the seam, there the "roof nodules" are more frequent than usual in the shales above.

"Erratics" in Coal bear no Relation to "Coal Balls."—While discussing the theory that the "coal balls" have drifted or been brought into their present position by rivers, it is necessary to refer to the blocks of granite and quartzite which have undoubtedly been brought from a distance and deposited in the coal. These have been found embedded in the actual coal in a number of different seams, and have often been described in the literature, see PLANT ('76), SPENCER ('87), RADCLIFFE ('87), and many others; while a number of general references to the subject have been collected by STUR ('85) in his important paper on the stone masses found in coal.

These erratic blocks are found in a number of seams in all parts of the world, but we have no record of their occurrence in the true "Bullion seam." The view which is now generally held is that these masses owe their present position to having been transported in the roots of drifting trees which may have mingled with the other coal-forming material. They do not affect the discussion of the origin of the calcareous plant-containing masses any more than the similar granite boulders which are sometimes found in limestone (see BALL ('88)) affect our views on the formation of limestone beds, for they are foreign bodies which have drifted in through some accident of local conditions. We mention them here, however, because at first sight it might appear that if a mass of quartzite could drift into coal, then the "coal balls" themselves might have been transported. Every point in the structure and occurrence of the erratics, however, shows them to be fundamentally different in nature and origin from the "coal balls," so that they will receive no further consideration in this paper.

To return to the consideration of the facts illustrated by the huge mass containing plant remains at Shore. Throughout its substance, as is generally the case with the normal "coal ball," there are preserved numbers of plants of different kinds. The plant scraps are also generally closely packed, so that practically all the substance of the coal ball contains plant tissue, the small interspaces being filled with nearly pure and almost transparent (when in section) mineral carbonates.

Nodule in Floor contains only Stigmarian Rootlets.—A nodule, showing a considerable contrast to this appearance, was found *in the floor* below the huge mass in the seam at Shore. Externally, this floor nodule had all the characters of a typical coal ball, being about 9 inches in diameter and of a very regular spheroidal shape. This nodule was the first to be found in the floor, and was therefore very carefully examined; a few others have been found since, and have the same characters. When cut open it revealed no plant structures except *Stigmaria* (axis and small rootlets); moreover, the matrix was very opaque and impure, and was shown by chemical analysis (see Table IV, p. 197) to contain a quantity of mud. As is perfectly clear from the analyses and structure of the true coal balls, they do not contain mud, and though Stigmariæ are very common in them, they are seldom the only plants present. Thus in the floor nodule we see a structure differing from the true coal ball in just those details which we should expect from what is already known of the nature of the plants found in the seats of coal seams containing roots of plants. Had the coal balls owed their shape and position in the seam to transport by water, we must imagine the stream also bringing some balls showing the very characters of the floor of the seam, separating from the seam nodules and depositing them in the floor, while the purely plant-containing ones took their place in the seam. Such selective power on the part of palæozoic streams is obviously inconceivable, and we must accept the floor balls as a very strong argument in favour of the view that the concretionary action took place *in situ*, and though generally arising only in the coal and among the plants there, that at times it originated in the floor below.

Nodules in the Roof.—It is now of importance to mention the well-known roof nodules which contain the marine shells so characteristic of the seams in which true "coal balls" are found. The typical roof is composed of black shales, in which the nodules are to be seen directly above the coal, sometimes even pressing down upon it so as to leave their imprint on the surface of the seam. These nodules vary considerably in size, but on the average are of larger size and more uniformly symmetrical than those in the coal. Such a nodule, of considerable size, is seen at R, fig. 4, Plate 17.

Each nodule has the form of an oblate spheroid, and lies in the shales so that its greatest diameter is parallel to the bedding plane. When cut through, these nodules often show a distinct though very fine bedding in the same direction as the bedding of the shales, and frequently the small Goniatites within them congregate in bands along the planes of this bedding (fig. 16, Plate 19). These facts prove that the nodules

must have been formed *in situ*; had they originated elsewhere such an arrangement of the bedding would be impossible. The fact that the floor and the roof nodules are formed *in situ* lends support, were it needed, to the argument that the seam nodules were also formed where they are found.

In these roof nodules isolated plants are also to be found in which the tissues are partly excellently preserved. The plant tissues are generally completely surrounded, and may even be partly penetrated by the fine Goniatite-containing mud which forms the matrix of the nodule. These plants have evidently drifted into the silt of a sea bottom—but they will be considered later (see p. 204, Section V).

Minute Structure of Coal Balls.—A block of coal containing a number of small "coal balls" yields a very instructive specimen when cut across, the surface sand-papered, and then treated with hydrochloric acid. The acid brings out the structure of the calcareous masses by whitening them, so that they stand out clearly from the black background of the coal (see figs. 2 and 6). The roughly circular form of the coal balls is already well known, and has been described and figured by STUR ('85), BERTRAND (: 06), and others. More minute examination, however, shows that the smooth roundness is only apparent, and in many cases does not describe the form of the structures in detail (see fig. 6, Plate 18).

Delicate and Irregular Edge of many Coal Balls.—Far from showing anything approaching a water-worn smoothness, they reveal a very delicately jagged edge, sometimes extremely irregular, with long fragments of plant tissue projecting from the main mass, these fragments being sometimes very well preserved. Had the "coal balls" been rolled as pebbles, even once or twice after fossilisation, these sharp corners would have been broken off. Such appearances, however, are innumerable; almost any block will reveal something of the kind, so that this point alone proves beyond dispute that the coal balls are not "pebbles." Such a block as is figured (fig. 7, Plate 18) shows the small and irregular form of a number of the coal balls, while in fig. 12, Plate 19, we see delicate mineralised strands *connecting two nodules*, which must have assuredly been broken had those nodules been rolled about.

Continuity of Plant Tissue in adjacent Balls.—Mr. LOMAX has stated (: 02) that "we should have certainly found, where we had an abundance of nodules, that these stems would have been continued from nodule to nodule; but that is not so. . . . The natural conclusion is that the various portions of plants have been carried into their present positions after being broken in fragments and before petrifaction, or they have been carried from a parent bed after petrifaction." In the course of our work, however, we have had the good fortune to meet with several cases in which the stems *are* continued from nodule to nodule, as we should expect. These examples are not common, but a very clear case is figured in fig. 11, Plate 19. In this specimen, at B and B′, are seen two clearly distinct and rounded nodules. In each of these two nodules are the parts of a single *Lyginodendron* stem, while between them the

streak of coal probably represents the lost tissue of the centre part of the stem. Nothing could more clearly demonstrate that the two nodules B and B′ must have been forming at the same time round different centres, and enclosing the same stem from two opposite sides. That they did not meet and form one big mass, but left the centre scrap of the stem to form coal, is a fortunate chance which cannot be explained. In this same block masses C and D suggest forcibly that they both represent portions of the same *Stigmaria*, though the case is not so convincing as is that of A and B. We observed that the *Sigillaria* at present being described by Mr. ARBER showed the same continuity in the block, but unfortunately it was not photographed, and it was cut in a direction which destroyed this evidence. A clear case is to be seen in fig. 10, Plate 19, where several adjacent nodules contain parts of the same plant tissue, undoubtedly from a single plant. We have noted other cases, and though the occurrence is certainly not common (as one must expect when the general fragmentary character of the tissues and the scattered distribution of the nodules, as well as the many slight later movements evidenced by the common slickensiding are taken into account), the above instances suffice to prove that the same stem *does* run through two or more nodules. As this result would be quite impossible had the nodules been carried even a short distance, it affords proof that the coal balls were formed where they are found.

The continuity of the tissues of a plant preserved in a nodule into the surrounding coal is another argument for the same conclusion. This is a condition not commonly met with, though it has been observed by us.

Summary of Points observed in the Mines which prove the in situ *Origin of Coal Balls.*

We may here shortly enumerate the main points drawn from this study of the coal balls in the mines, which afford proof that the coal balls were formed as concretions in the seams in which they are now found, and have not been derived from other sources :—

(*a*) Concretionary structure clearly shown (figs. 6, 10, and 13, p. 175).

(*b*) Size of some masses too great for transportation (p. 174).

(*c*) Shape of similar masses makes transportation *as such* impossible (pp. 176 and 177).

(*d*) Nature of "floor" and "roof" nodules (p. 180).

(*e*) Delicate projecting fragments of tissue on coal balls prove that any rolling after formation was impossible (p. 181, figs. 7 and 12).

(*f*) Continuity of same stem through two or more adjacent nodules (p. 181, fig. 11 and fig. 10.

(*g*) Continuity of tissue from nodule into surrounding coal shows they cannot have moved since petrifaction (see above).

Section III.

Geological Horizons of the Beds containing the "Coal Balls."

Views of other Investigators.—As has already been stated in the introductory section, most of the earlier work bearing on the geology of the coal balls was published by Binney. Before grasping the importance of the coal balls he had long worked on the geology of the Lower Coal Measure beds and had paid particular attention to the marine shells occurring in some of them. Many of the best preserved and most important of these shells, such as "*Goniatites Listeri*," "*Pecten* (*Aviculopecten*) *papyraceus*," and others of undoubted marine habitat, he found in "over five distinct beds" in the Lower Coal Measures (see Binney ('40)). Thus we are prepared to find in his paper, published by the Palæontographical Society ('68), that he states that the plant-containing bullions which occur associated with the marine shells are to be found in several horizons (see p. 12 of his paper, where he tabulates the beds). On p. 14 he states, "so far as my experience extends, the occurrence of nodules in the coal is always associated with that of fossil shells in the roof, and therefore may probably be owing to the presence of mineral matter held in solution in water and precipitated upon, or aggregated around, certain centres in the mass of vegetable matter now forming coal before the bituminization of such vegetables took place."

This shows that Binney considered that the plant nodules were formed in the coal, and that he believed that the process of mineralisation yielding the nodules must have taken place several times in the course of the deposition of the Lower Coal Measures.

Binney's investigations, however, were made at a time when the detailed work of correlating the numerous beds of the Coal Measures had only just begun, and therefore many of the names and horizons he gives have been revised and altered by later authorities. Hence his views as to the horizons of the nodule-bearing beds cannot be used in support of our argument. The modern view, which replaced his, recognises but one horizon in which plant nodules in the seam, with "roof bullions" containing marine shells in the roof, are to be found. On this basis the seams in the Lower Coal Measures are correlated and arranged in series.

In the Geological Survey Memoir, Hull ('64) describes the district round Oldham, and gives (p. 16) a tabulated section of the beds forming the Lower Coal Measures, *i.e.*, those which lie between the top beds of the Millstone Grit and the Arley Mine, the latter being the lowest of the Middle Coal Measure seams. In this series the "Bullion Coal" or "Upper Foot Mine" finds its place as a distinct horizon above the Gannister. Hull says (p. 19) that it, "although so thin, is wonderfully constant all over the district." Cash and Hick ('78) also concur in this opinion. In his paper on the general aspect of the Lower Coal Measures of Lancashire, Wild ('92) points out the difficulty of correlating the beds in these series, owing to the large amount of local variability even in the bed taken by Professor Hull as the base of the series, viz., the Sand Rock or Feather Edge Coal, which is usually associated with the

Rough Rock. WILD points out the marked and constant features of the "Bullion Coal" with its marine roof, and takes this bed as a fixed horizon from which the other seams can be correlated up and down in the series. He fixes this bed as a datum line, because it is much more constant and readily recognised than Professor HULL'S Sand Rock Mine. He says (p. 373): "I have, therefore, chosen not as a base, but a datum, a seam of coal with features in it and over it more constant and definite in distinctness than a variable bed of sandstone such as the Rough Rock." He quotes in support of his view the names of many men distinguished in local geology, and those of Messrs. NIELD, BUTTERWORTH, and EARNSHAW, known to palæobotanists (p. 370), who "all spoke decidedly, that to their knowledge no other mine contained the same sequence of palæontological features as this coal, viz., dark shale forming the roof, containing marine shells in a flattened state, and also the concretionary balls containing similar shells, but preserved in their natural form, and balls with well preserved fossil wood in the coal itself."

In 1898, BOLTON published the results of his work on the complex nomenclature of the seams of the Lower Coal Measures, and in this valuable paper the "Bullion Coal" is treated as a definite horizon,* as it is in his paper (BOLTON : 04) on the palæontology of the Lancashire Coal Measures, which we have already quoted (see our Section I, p. 170). Among the miners and overseers this view is equally prevalent, as we have learnt from many conversations, and as is well illustrated by the remark made by Mr. LOMAX (: 02): "As we all know, there is only one seam of coal in which we find these nodular concretions."

"Circular" Argument used in Support of the View for but one Horizon.—If carefully examined, the argument on which this view is founded is seen to be a "circular one." *Goniatites* and *Aviculopectens* are not in any sense restricted zone fossils, they have a wide range and are, therefore, useless for determining an horizon. Even when all the factors are taken together, as given in WILD'S paper, the argument is not strong, for it appears that whenever the "bullions" and roof "baum pots" are

* It may be useful for those whose local knowledge of the beds is not very great to have a tabulated list of the Lower Coal Measure seams. The following list is drawn from BOLTON'S (: 04) paper, in which he uses the best known names of the coals :—

"Pasture" and other thin coals.	(Top of series, next coal above being the Arley Mine, *i.e.*, Middle Coal Measures.)
"Upper Mountain Mine."	
"Fireclay" Coal.	
"Bullion" or "Upper Foot" Seam.	These may fuse and form one seam, called the "Mountain 4-feet" Seam.
"Gannister" Seam.	
"Lower Foot" Seam.	
"Bassey" Seam.	
"First Coal."	(Lowest of series, below comes the Millstone Grit.)

It must be noted that all through the series are very thin coals (locally thickening in some cases) which have been ignored.

found in and above a seam, then it is at once called the "Bullion" or "Upper Foot" Seam, and *consequently* it is stated that the structures occur only in the one horizon, viz., the "Bullion" Seam!

In the course of our work certain facts have been discovered, the details of which are given below, and other facts have been drawn from the literature on the subject, which appear to demonstrate clearly that this horizon is not so unique as the workers just quoted have believed it to be. A strong point against their view is found in the occurrence of identical structures in the Continental and American coals (see p. 191 and fig. 15, Plate 17), which are undoubtedly horizons different from the English "Bullion Seam." This alone would be enough to prove that the conditions which formed the "coal balls" had occurred more than once in the history of the world, and that as a consequence all our localities in England where they are found need not *necessarily* be of the same age and horizon.

New Horizon at Stalybridge.—We discovered a new locality for the true "coal balls" and "roof nodules" in a small seam at Stalybridge. The exact position is marked on the map at ×, Map 1. Typical roof nodules with Goniatites were found lying on the surface slope of the steep bank which runs down from the main road to the paper mill at the edge of the river. The slope was partly grass grown, and showed signs of many small slips of earth and shale, so that it was impossible at once to locate the spot whence they came. Careful search revealed true coal balls, but they were not *in situ*. Mr. HARGREAVES, the owner of the mill and the slope, generously placed his workmen at our disposal, and allowed us to excavate likely spots on the ground. After a number of visits we found that a roadway was being cut just where we wished to dig, and fortunately this exposed a splendid section of the small coal seams and thick clays, lying undisturbed. We obtained a cutting at the right spot to find the seam we sought, which proved to be a very poor and thin coal, containing a number of perfectly typical "roof nodules" and true "coal balls."

In this valley the beds dip obliquely east and west, and are exposed along its length in a very typical section. The succession of the rocks here was described by Professor HULL ('64) who surveyed the district. Below the Woodhead Hill Rock (a

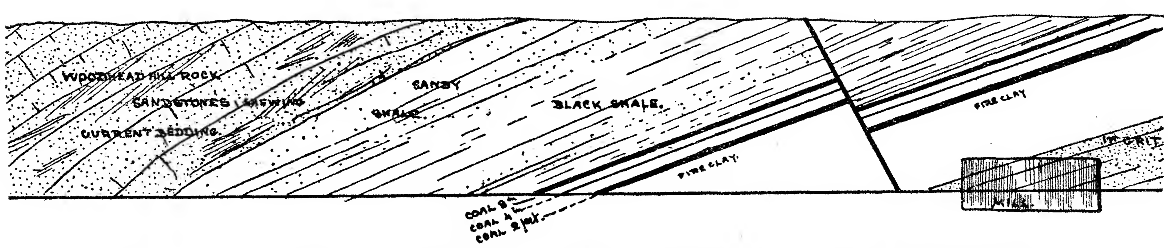


FIG. 3.—Rough diagram illustrating positions of beds in the section at Stalybridge.

very thick bed of sandstone, text-fig. 3) he describes but one seam, the "First Coal," and under it a fire-clay or potters' clay.

The outcrop of our coal seam was perfectly clear, and was readily seen to be *below*

the thick beds of the Woodhead Hill Rock, which are quarried up the hill. A little further up the valley, the Grit is exposed (see map and survey memoir) so that the position of the bullion-containing seam is clearly indicated below the Woodhead Hill Rock and above the Grit. Between it and the Grit were one or two very small seams of coal with very thick underclays: the lowest of these was two feet thick and had a splendid underclay. This seam is probably the one marked in the six-inch Geological Survey Map, the others being too small to be worthy of notice except for some special purpose. The series was as follows :—

Roof, with Goniatites, roof nodules, etc.
Coal seam, 8 inches, many true coal balls.
Underclay, 5 feet 9 inches.
Coal, very thin.
Underclay, 13 feet 9 inches.
Coal, 2 feet.
Underclay, 8 feet + ?

All these beds were undisturbed and lay in their natural bedding. From the workmen we learned that these underclays had been worked in the past, a point in which this seam resembles that at Hough Hill and differs from the usual "Upper Foot Mine."

Reference to the map (text-fig. Map 1) west of the outcrop will at once show that the seam lies a very considerable distance *below the Gannister*, which in its turn lies below the true "Bullion" or "Upper Foot" Seam.

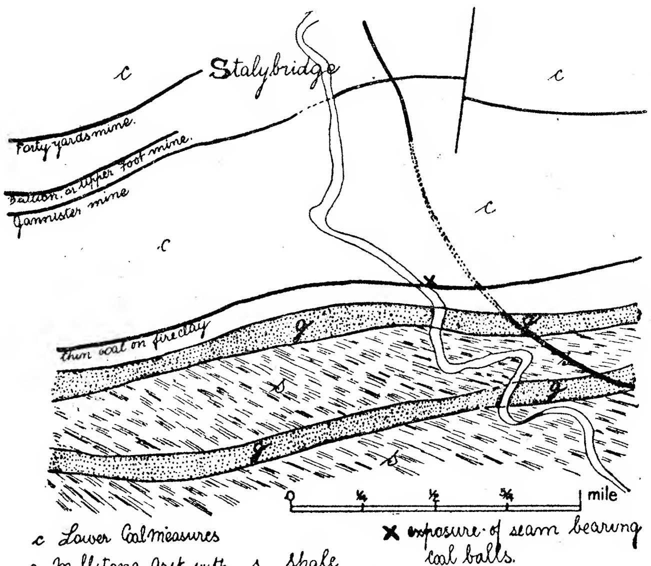
This would show (assuming the Survey Map to be correct) that at Stalybridge we have a coal seam with true coal balls and roof nodules, but of a horizon lower than that of the recognised seam containing these structures.

Now, if the line of its outcrop be followed on the map (Map 2) to the south, it will be seen that it cuts directly through the spot where the workings of the mine at Hough Hill are situated, a mine which has long been known as one of the best sources of the "coal balls." It was then necessary to prove whether the actual coal of the Hough Hill Mine outcrops at this point, or if it be worked with a long gallery leading to the coal. Had the latter been the case it might very well have been that the workings actually reached the Bullion Seam itself, but in the former case the coal certainly comes on the Stalybridge outcrop.

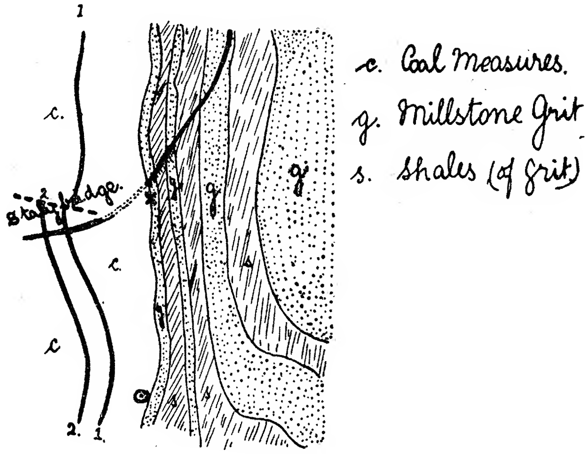
We carefully examined the whole slope of the hill, and questioned the workmen, and from JOHN RHODES, who was working in the mine at the time, we learned that the mouth of the pit was the actual beginning of the coal seam which they worked, that the mouth was at the outcrop, and that they simply followed down the dip of the beds into the hill. In the pit also they work for fire-clay below the coal. Hence it is clear that the Hough Hill Seam is the same as the one which outcrops at Stalybridge, and it is also proved that the Hough Hill–Stalybridge Seam is a coal on an horizon much below the "Upper Foot" Mine.

It may be thought by some that undue reliance has been placed on the Survey

mapping. We would remind them that this section along the Tame Valley is so well exposed (it is quoted as a standard section) that even without the map the position is clear when one is in the field; further, that the thick workable underclay is a character which is not typical of the "Upper Foot" Seam, and its occurrence below the Hough Hill–Stalybridge Seam is enough to suggest that it is a distinct one; and still further, that the onus of proof now lies on those who do not accept the map and this evidence.



MAP 1.—Stalybridge reduced from 6-inch Survey Sheet Lancashire 102.



MAP 2.—Stalybridge and Hough Hill on the 1-inch scale. At × the exposure at Stalybridge, and at ⊙ the outcrop of the seam (*i.e.*, pit mouth) at Hough Hill. This shows that the two outcrops are those of the same seam, which lies normally below the Gannister. Sketched from Survey Sheet 88.

It is of interest that Hough Hill has been recorded as a source of "coal balls." GEORGE WILD ('92), p. 368, states that he made "the discovery that a bed of coal was being worked at Hough Hill, a little south of Stalybridge, 700 to 800 feet above sea level, in which these bullions ('coal balls') occur . . . which were of a very dark brown colour and somewhat pyritous, but which I suspected were of the same character as those met with in the Bullion Coal. . . . The roof of this seam is a black shale of variable texture, but barren of fossils except in the 12 inches next the coal. . . . This seam, I was informed, was supposed to be much below the Gannister Coal, and, in the absence of balls, 'baum pots' in the roof containing Goniatites, etc., which I was informed had never been seen, I felt inclined (though reluctantly) to accept the position assigned to it as correct. . . ." He adds that he spoke of it to palæobotanical friends, who assured him that some Goniatites at least would be found there, and that it must be the same horizon as the Bullion Seam, because that was the only one to contain these structures. WILD finally obtained Goniatite nodules from this pit, and adds, p. 370, "in the absence of some convincing evidence to the contrary, I feel constrained to fix this seam as the representative of the Bullion Coal."

As we have just proved that it lies below the Gannister, there is no longer any necessity to accept this somewhat strained conclusion. WILD evidently felt that his argument was not quite secure, for on p. 374 he says, "should it eventually be proven that this seam at Hough Hill is not identical with the Upper Foot or Bullion Coal, it would affect somewhat the length of the datum. . . ." He is far from inclined to accept this, however, as it weakens the position of the Bullion Seam as a datum line, but as a true scientist he recognises the possibility, and in the following words shows his openness to conviction: If the recurrence of nodules in the coal of different seams could be proved, "It would not, I feel assured, be hoping too much, that phenomena, indicating a repetition of features so remarkable in connection with the formation of a bed of coal, would, under the penetrative research of modern science, lead to a tolerably fair conception of the nature of the forces in operation."

This Hough Hill–Stalybridge Seam alone is sufficient to prove our contention, viz., that the "coal balls" are not confined to a single seam and horizon, but we have other instances to quote in further support of our views.

A fact which is very generally known, but which has not been described in detail, and of which the bearing in this connection is important, is as follows :—

Over a large area of the North Lancashire Coalfield, the "Bullion" Seam and the one below it (locally called the "Gannister" or "Mountain" Mine) do not lie separated from each other by a depth of rock, but approach and finally fuse into one seam, which is thicker than the two seams separately. After the union is complete, they are locally considered to be one seam, and are known as the "Union" or "Mountain 5-feet" Mine. Where the two seams are perfectly joined, the roof is of course common to both, and is that of the Bullion Seam, having Goniatite nodules in its shales.

Coal Balls in the Gannister Seam.—The interest for us in the junction lies in the fact that throughout both Bullion and Gannister (after the Union) true coal balls are found in the coal, and furthermore, coal balls are found in the Gannister itself before the junction, when the beds approach each other closely.

This is a fact which has important bearings on another subject, and will be referred to again (p. 195), but for the moment we are concerned with the point that the coal balls are found in the horizon below the Bullion Mine.

AITKEN, BOLTON, and others have mentioned the junction of these seams, which stretches over a considerable tract of country, but may be seen best at the Old Meadows Pit at Bacup, where the workings expose the seams particularly well. Owing to the kindness of Mr. ILLINGWORTH LAW we were able to make detailed observations in this pit, on which the following account of the beds is based :—

The two seams (*i.e.*, the "Bullion" and "Gannister") enter the hill separated by a dozen feet of rock; along the roads of the mine they are seen to approach each other gradually until they meet. In the last stage before their fusion they

approach very slowly, reducing the distance between them but 8 inches in 29 yards (see fig. 4 in text).

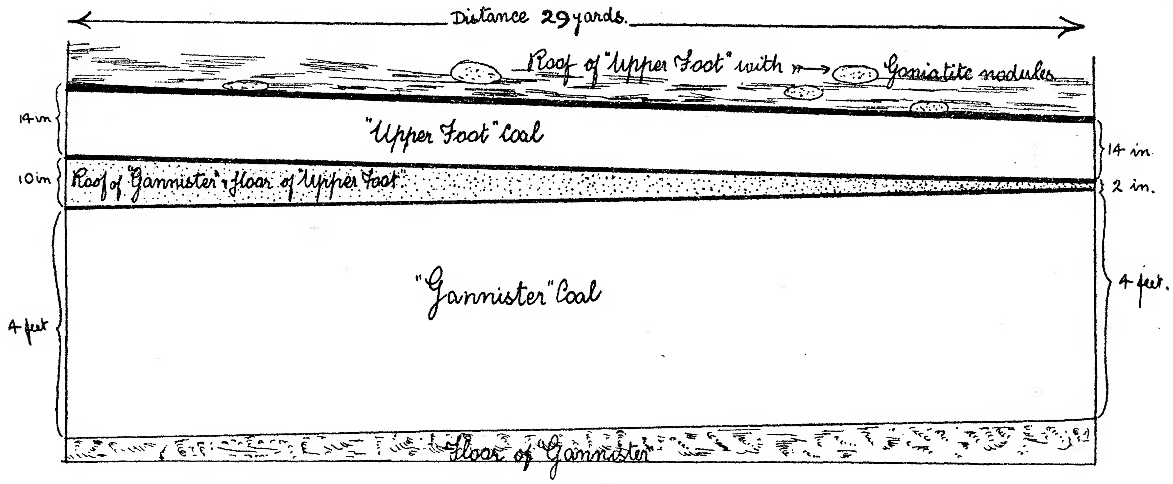


FIG. 4.—Diagram showing slow approach of the two seams at Bacup.

Where the distance between the two seams is reduced to about a foot or less we find that true coal balls appear in the Gannister Seam, as well as those in the "Upper Foot." Some of these reached a large size, *i.e.*, with a diameter of a foot or more, and were perfectly typical in every way.

A diagram illustrating this is given in fig. 5 in the text.

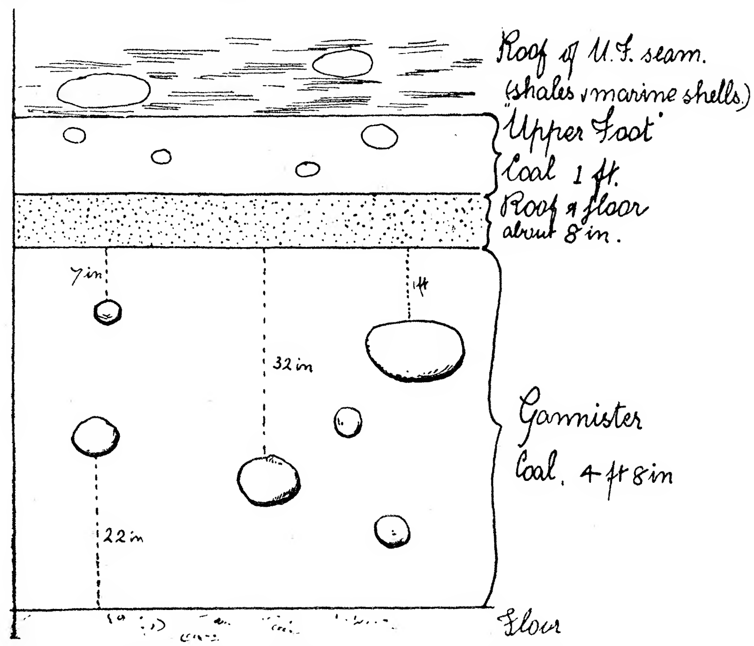


FIG. 5.—Showing "coal balls" in Gannister Seam near junction.

It will be noticed that they lie throughout the thickness of the Gannister Coal, as they do in the typical Upper Foot Seam. In the beds between the two coals no

marine shells or roof bullions were found, but the roof above the Upper Foot was shaly and contained Goniatite nodules in the normal way. The bullions are still found after the two coal beds have fused, leaving but an inch "dirt bed" between them, such as may be found in any coal. For our present contention the case illustrated in text-fig. 5 is all that is required to show that coal balls may occur in the Gannister Seam.

The Great Harwood Seam.—The lenticular patches of stone which are found in the coal at the Great Harwood Colliery have been described on p. 176. It was there shown that, although they differ in many ways (see also Section IV and Table III of analyses), yet they contain plant fragments petrified in carbonate of lime and magnesia which replace the coal in the seam, and therefore they must be considered as coming within the category of "coal balls." It is not easy to determine the geological horizon of this seam, because exact information is not obtainable owing to the position of the beds and the relative isolation of the basin in which the coal lies. Information which the owner and the manager kindly supplied from their memory of the beds seen during the sinking of the shaft and the making of the first road seems to indicate that the seam with these structures is one lying just above the true "Bullion" Seam.

As there is this uncertainty about the exact position of this seam, it is not used as an argument regarding the various horizons in which the "coal balls" occur, although the general inference is in favour of our view.

"Coal Balls" in the Millstone Grit.—An important case is next to be described showing that true "coal balls" with roof nodules with Goniatites occur in a seam in the Millstone Grit, a group of rocks below the Lower Coal Measure series.

Unfortunately, these specimens were not seen *in situ*, as the mine from which they were brought up has long ceased working, and they are only to be seen on the pit heap. None the less, specimens occurring in numbers on an old pit heap afford fairly satisfactory evidence of their origin. The pit is near Laneshaw Bridge by Colne (see Sheet 49), and was worked in 1800. As is seen on the map, the shaft lies on the shales below the 1st Grit or Rough Rock; it is stated that the coal was at a distance of but 30 yards, and hence must have been in the grits; possible beds of the Lower Coal Measures are considerably over that distance away from the shaft. The coal balls and roof nodules are of quite typical form. Hence, although there is not absolute certainty in the conclusion, there seems very good ground for believing that we have here coal balls from an horizon in the 1st or 2nd Grit, and hence considerably lower than any other recorded.

Middle Coal Measures.—In the Middle Coal Measures of England we have as yet no clear case of typical "coal balls" occurring in any of the beds. There is, however, the case of the Dolomite masses in the Wirral Colliery, which, as we pointed out (p. 176), represent the results of a process which in its essentials is the same as that which gave rise to the true "coal balls." Now the Wirral Coal is undoubtedly of

Middle Coal Measure age, though the exact correlation of the seam is not clear. By the manager of the mine it was considered to be the equivalent of the Arley Mine, which is the lowest of the Middle Coal Measure series.

Summary of Localities and Horizons Yielding "Coal Balls."

In the preceding pages we have proved that the view that the coal balls are confined to the restricted horizon of the Bullion Seam is one which is no longer tenable.

The following list gives the horizon and localities of formations in which typical and undoubted "coal balls" have been found :—

Formation.	Horizon.	Locality.
Millstone Grit . . .	Shales below "Rough Rock," *i.e.*, First Grit	Laneshaw Bridge (p. 190)
Lower Coal Measures .	"First Coal" (?) below Woodhead Hill Rock	Hough Hill–Stalybridge (p. 185)
	"Gannister"	Bacup and elsewhere (p. 188)
	"Upper Foot" or "Bullion" Seam . .	Many localities in Lancashire and Yorkshire (p. 170)
	Flotz Isabella	Westphalia
Upper Coal Measures .	Radstock Series and above.	Banat, Hungary
		Orlau

Other structures which, though not typical *balls*, are parallel in their geological character, are as follows :—

Formation.	Horizon.	Locality.
Base of Carboniferous system . . .	(?)	Iowa, U.S.A., Plate 17, Photo 5
Calciferous Sandstone	(?)	Burntisland
Lower Coal Measures.	Above Upper Foot Seam (?). .	Accrington (p. 190)
Middle Coal Measures	Arley Mine (?)	Wirral Peninsula (p. 176)

Section IV.

Chemical Composition and Formation of "Coal Balls."

In the last section, the general consideration of the geological conditions of the occurrence of the "coal balls" *in situ* in various localities led to the conclusion that they are not confined to one distinct horizon, even in the Lancashire district itself, but that, on the contrary, they occur in beds of different ages, which have been deposited both in different places and at different times, though they have not yet been found in beds more recent than the Carboniferous System.*

* The subject is receiving the special attention of one of us (M. C. S.), who is making special efforts to discover mesozoic "coal balls." The officers of the *Geological Surveys* of both England and Scotland are now kindly looking out for them, so that it is possible that before long we may be in a position to make a further extension of the lists of horizons at which they occur.

We have also found (see pp. 173–175), that in their external characteristics even the true "coal balls" vary very greatly, and may take the form of spheres of minute size, or of large rounded masses a foot or more in diameter, or of larger irregular masses of the most various shapes and sizes.

Variability in Chemical Composition.—In their chemical composition we find also a considerable variety, not so much in the minerals forming them as in the proportions of the principal minerals. Analyses are given (p. 193) in Table I, which show that, even among the true coal balls of a single locality, though the chief compounds are fairly constant in their appearance, the proportion in which they occur is very various indeed. Thus, in Analysis III, Table I, the amount of calcium carbonate is 49 per cent., while in Analysis VI it is 91 per cent., and these, though from different localities, are yet from the same horizon. Analyses VI to X are made from coal balls taken from the seam in Shore Mine, from points less than 100 yards apart in horizontal distance, and from a coal that seldom exceeds 1 foot in thickness, yet we see a range of from 56 per cent. to 91 per cent. in the case of the calcium carbonate contained in these nodules.

For the first time in dealing with the subject of coal balls, large numbers of analyses have been made and tabulated for comparison, and as a result it becomes evident that very little weight is to be attached to the variations in the percentages of calcium and magnesium carbonate (the two most important minerals) in the structures.

In the past but few analyses have been published, and it has been the custom to repeat that given by BINNEY ('54) as typical of the English nodules, and that of WEISS ('84) of the Westphalian. Hence it has not been generally recognised how wide may be the range in chemical composition even in nodules of identical source. This perhaps led to FELIX'S ('86) conclusion that the Westphalian nodules were of a different nature to those from Orlau, described by STUR ('85). He quotes the analyses side by side for comparison, and draws his conclusion from the differences in the percentages of the minerals composing them. We quote these analyses in Table II (Nos. III and IV), and it will be seen at once, on comparing them with those in Table I, that the differences between them are not so great as are those between specimens from the single seam at Shore Mine, or even between specimens found within a few yards of each other.

The comparison of the analyses will be referred to later on (p. 195); for the present we wish to point out that the variety which exists in the structure of the coal balls, and particularly in their chemical composition, is not of a fundamental nature.

Before attempting to consider the formation of the coal balls, it is necessary to realise fully the importance of the few factors that show in common. Of these, the chief is the constant association of roof nodules with Goniatites in the shales above the coal seam containing true "coal balls."

TABLE I.—Analyses of True "Coal Balls" made specially for this research.

	I. From seam near Bacup, L.C.M. Upper Foot Mine.	II. Same locality as I.	III. Same locality as I.	IV. Same locality as I.	V. From the new horizon at Stalybridge.	VI. From the Upper Foot Seam at Shore. Specimen D.	VII.* Same mine as VI. Specimen adjacent to D.
Calcium carbonate, $CaCO_3$	51·188	52·378	49·355	51·136	87·827	91·09	87·80
Magnesium carbonate, $MgCO_3$	42·820	39·884	39·682	40·577	6·212	—	3·75
Ferrous carbonate, $FeCO_3$	2·342	2·973	2·220	2·247	1·026	3·95	1·10
Ferric oxide, Fe_2O_3	—	0·113	—	—	—	—	—
Manganous carbonate, $MnCO_3$	0·521	1·167	0·597	1·306	0·853	—	—
Alumina, Al_2O_3	traces	traces	—	—	traces	—	0·49
Calcium phosphate, $Ca_3P_2O_8$	0·525	traces	0·222	0·542	traces	—	—
Iron pyrites, FeS_2	0·339	0·783	3·273	0·532	1·430	—	—
						Insoluble residue.	—
Silicate of alumina (clay)	0·119	0·000	0·053	0·248	0·000	1·09	—
Carbonaceous matter	1·855	2·281	4·064	2·789	2·579	3·58	—
Free moisture	0·264	0·283	0·446	0·633	0·100	0·07	—
Total	99·973	99·862	99·912	100·010	100·027	99·69	—
Specific gravity	2·774	2·731	2·713	2·671	2·663	—	—

	VIII.* Same mine as VI. Specimen S 5.	IX.* Same mine as VI. Specimen B.	X.* Same mine as VI. Specimen E.	XI.* Upper Foot horizon, from "Clough Foot," Dulesgate.	XII.* Hough Hill.	XIII. From Little-borough Shore).	XIV. Same as XIII.	XV. From new horizon at Laneshaw Bridge.
Calcium carbonate, $CaCO_3$	56·55	88·30	81·00	55·3	54·60	56·256	54·910	50·292
Magnesium carbonate, $MgCO_3$	11·70	4·90	4·45	7·9	4·50	28·920	26·292	39·389
Ferrous carbonate, $FeCO_3$	5·55	1·53	1·55	2·17	5·20	9·480	12·871	3·480
Ferric oxide, Fe_2O_3	—	—	—	—	—	—	—	0·328
Manganous carbonate, $MnCO_3$	—	—	—	trace	—	0·566	0·974	0·549
Alumina, Al_2O_3	0·95	0·64	0·93	0·33	0·95	—	—	0·184
Calcium phosphate, $Ca_3P_2O_8$	—	—	—	—	—	absent	traces	0·092
Iron pyrites, FeS_2	—	—	—	—	—	—	—	3·012
Silicate of alumina (clay)	—	—	—	—	—	0·470	0·646	—
Carbonaceous matter	—	—	—	—	—	3·763	3·880	2·773
Free moisture	—	—	—	—	—	0·153	0·347	—
Total	—	—	—	—	—	99·608	99·920	100·039
Specific gravity	—	—	—	—	—	2·569	2·795	2·78

* In these analyses only the most important compounds were determined, as the complete analyses were not essential, and would take much time.

TABLE II.—Analyses of True "Coal Balls." (Drawn from the Literature for reference and comparison.)

	I. HOOKER and BINNEY ('54). BINNEY ('68). This is of wood from nodule.	II. Nodule itself. BINNEY ('68).	III. WEISS ('84), of Westphalian nodule quoted by FELIX ('86).	IV. STUR ('85), from Orlau Seam nodule.	V. STUR ('85), mass from Szekul, in Banat.	VI. Stocks (: 02), "Upper Foot" nodules, Lancashire and Yorkshire.	VII. Same as VI.
Calcium carbonate, $CaCO_3$	76·66	45·610	54·1	56·52	11·61	64·41	82·32
Magnesium carbonate, $MgCO_3$	12·87	26·910	35·7	10·02	5·90	1·82	0·61
Ferrous carbonate, $FeCO_3$	—	—	0·2	15·60	62·64	6·00	0·30
Ferric oxide, Fe_2O_3	4·95	13·578	0·1	—	—	—	—
Alumina, clay, etc.	—	—	—	0·89	2·30	0·33	trace
Iron pyrites, FeS_2	*0·73	11·650	2·6	—	—	21·58	12·16
Silica	—	0·230	—	—	—	1·16	1·20
Sulphates of potash and soda	—	1·620	—	—	—	—	—
Calcium sulphate	—	—	—	—	—	0·32	0·03
Carbonaceous matter and H_2O	4·95	0·402	7·1	16·80	12·60	(H_2O) 0·25	(H_2O) 0·30
Residue after ignition	—	—	0·2	0·17	4·95	—	—
Total	100·16	100·000	100·0	100·00	100·00	95·87	96·92

* This is given as iron sulphate, but in all other cases iron sulphide is the form present, and it is probably a misprint in the original.

NOTE.—In quoting analyses where MgO, CaO, etc., and CO_2 have been given separately, they have been given in the form $MgCO_3$, etc., to facilitate comparison with our analyses.

Universal Marine Roof.—As will be seen on reference to Section III of this paper, the coal balls are always associated with evidences in the roof that indicate that the seam had been immediately submerged under sea water. The evidence is usually found in the large "roof nodules" which contain *Goniatites*, in large numbers, as well as in the shales where *Goniatites, Aviculopecten* and other shells are compressed between the layers; these shells are well known to be *marine*. The constancy of this phenomenon is of prime importance, and appears in the British seams of different horizons in which coal balls occur; in the Westphalian beds the "roof nodules," as described, appear to be identical with those in our country, and afford equally certain evidence of marine conditions ensuing immediately after the deposition of the coal; while in Orlau, in Silesia, there were quite similar structures in the roof, as STUR ('85) makes clear in his account of the coal balls. Even in the case of the structures from Iowa, where Goniatite nodules have not been recorded, Mr. GRESLEY informs us that he found many marine shells and *Encrinites* close down upon the coal.

In fact, we might almost use BINNEY's words ('68, p. 14) and say: "So far as my experience extends, the occurrence of nodules in the coal is always associated with that of fossil shells in the roof."

A case which is of considerable importance in this connection is that described on p. 188, figs. 4 and 5. Here we see, even more clearly than usual, the connection that exists between the marine conditions succeeding the deposition of the coal (as evidenced by the marine shells in the roof) and the formation of the calcareous concretions containing plants in the seam. Here, in the Gannister Seam, which is otherwise without "coal balls" in its coal or marine shells in its roof, we see the coal balls appearing in a perfectly typical form, directly the Gannister comes near enough to the Upper Foot Mine to be within the sphere of influence of the marine conditions which prevailed while its roof was deposited.

No fact in the course of our work has stood out so clearly as that the "coal balls" owe their formation to the influence of sea water. In the light of this view let us further examine the chemical composition of the structures as revealed by the series of analyses.

Detailed Consideration of Analyses.

As Table I, p. 193, shows, the coal balls are principally made up of calcium and magnesium carbonates, in many cases in the proportion in which these carbonates occur in dolomite, though there is considerable variation. In general, the carbonates taken together, whatever their individual proportions may be, form 90 per cent. or more of the whole mass of the coal ball. In some localities, however, iron pyrites figures largely in the nodules, particularly in those found in the Halifax district, and there is commonly a small proportion of iron carbonate. It is an important fact that quartz is absent, and that the amount of alumina and silicates is so minute as to be a negligible quantity, except for purposes of minute analysis, thus showing that muddy or detrital matter was absent from the mass of material which was petrified as "coal balls," and that practically pure plant masses were mineralised by the dolomite or mixture of carbonates. The amount of carbonaceous matter left as such in the mass is very various, and it is probable that it depends on the state of perfection that the mineralisation had reached (see p. 200).

The presence of iron pyrites is so common in beds which are rich in fossils, and so frequently results from later reactions, that it need not be taken into account in dealing with the theoretical side of the question of the formation of the coal balls. As is seen from the tables of analyses, the percentage of pyrites varies; analyses are not quoted of this district, but it is easily recognised from hand specimens that the amount is unusally large in the balls from the Halifax district.

We have already had occasion to quote the case of the Wirral Colliery as being in some ways parallel to that of a mine with true "coal balls," and when now dealing with the analyses it may be well to note that they show a considerable

similarity in their composition, as will be seen on comparing the first three or four columns of Table I with Nos. II, III, and IV of Table III, the most important difference being the amount of carbonaceous matter which is so large in No. IV from the Wirral dolomite (see p. 178).

TABLE III.—Analyses of Structures found in various Coals, comparable with True Coal Balls.

	I. Mass from Accrington (see p. 176).	II. Specimens from the Wirral Colliery, quoted from STRAHAN'S paper (: 01).	III. Same as II.	IV. Same as II.	V. Block from Burntisland (see p. 191).
Calcium carbonate, $CaCO_3$	33·291	38·41	46·80	44·44	80·192
Magnesium carbonate, $MgCO_3$	2·479	30·09	38·83	27·78	3·967
Ferrous carbonate, $FeCO_3$	47·000	0·94	—	4·79	0·825
Iron oxides, FeO and Fe_2O_3	1·542	1·69	0·60	2·32	traces
Manganous carbonate, $MnCO_3$	0·092	0·53	—	0·86	1·146
Alumina, Al_2O_3	traces	0·34	0·15	0·34	traces
Calcium phosphate, $Ca_3P_2O_8$	0·781	—	—	—	traces
Iron pyrites, FeS_2	0·378	—	—	—	—
„ sulphate $FeSO_4$	—	—	0·15	—	—
Silicate of alumina (clay)	—	—	—	—	10·492*
Carbonaceous matter	14·429	4·09	2·99	17·80	3·051
Free moisture	—	0·55	0·45	1·29	—
Ignited residue	—	23·68	11·02	0·33	0·305
Total	99·992	100·32	—	—	99·978
Specific gravity	2·75	—	—	—	2·635

* Taken together with all the inorganic residue.

Composition of "Roof Nodules."—We have seen from the analyses how entirely free from detrital matter are the coal balls from the seam, in comparison with those we may now consider as the "roof nodules" from the shales above the coal. Analyses of the nodules are given in Table IV, p. 197, which show that the proportion of calcium and magnesium carbonates present varies in the same way as it does in the case of the coal balls, the only difference of importance in the composition of the two types of nodules being in the relatively large amount of silicate of alumina (clayey matter) which appears in the "roof nodules." In the coal balls the percentage of silicate of alumina averages less than 0·2 per cent. of the whole material, while in the roof nodules the amount is from 1 to 6 per cent., that is to say, from 5 to 30 times as much as in the coal balls.

It appears that, though otherwise very similar to the coal balls, they were formed under conditions less free from detrital matter, a point in which the analytical

TABLE IV.—Analyses of "Roof Nodules" or "Goniatite Nodules" found directly above the coals containing "Coal Balls."

—	I. From the new horizon at Staly-bridge.	II. Two analyses from same nodule. Inner part with fossil.	III. Two analyses from same nodule. Outer part, or matrix.	IV. From Shore (Upper Foot Mine).	V. Same locality as IV.	VI. Special nodule found in the *floor* (*cf.* p. 180).
Calcium carbonate, $CaCO_3$	84·700	52·664	49·259	86·41	86·2	65·234
Magnesium carbonate, $MgCO_3$	1·600	39·853	36·846	—	3·8	11·426
Ferrous carbonate, $FeCO_3$	2·448	4·926	6·681	6·59	2·20	7·610
Manganous carbonate, $MnCO_3$	1·808	0·465	0·894	—	—	0·256
Ferric oxide, Fe_2O_3	—	—	—	—	—	—
Alumina, Al_2O_3	0·216	—	—	—	—	traces
Calcium phosphate	traces	none	traces	—	—	traces
Iron pyrites, FeS_2	1·280	—	—	—	—	1·190
Silicate of alumina (clay)	6·447	and other insol. residue 1·081	and other insol. residue 3·961	insol. residue 4·72	4·31	8·614
Carbonaceous matter	1·473	0·776	1·706	1·80	—	5·465
Free moisture	0·000	0·200	0·302	0·18	—	0·200
Total	99·972	99·965	99·649	99·80	—	99·995
Specific gravity	2·666	—	—	—	--	2·56

results entirely support the conclusions previously mentioned in this paper (see p. 180).

Composition of "Floor Nodule."—The character and importance of the "floor nodule" has already been referred to (p. 180). The details of its chemical analysis are given in Column VI, Table IV, and it will be seen that it compares very closely with the average "roof nodule," except that the proportion of clayey matter is unusually high (approaching 9 per cent., *i.e.*, more than 40 times that present in the coal ball), a fact, however, which is in complete harmony with its position in the floor of the seam, where the only plant remains were roots penetrating the soil.

Large Amount of Magnesium Carbonate in "Coal Balls."—Any hypothesis which attempts to account for the formation of the coal balls must take into consideration the magnesium carbonate, which so frequently bulks largely in the substance of the mass (see Table I). In this respect, BINNEY'S ('68, p. 15) theory fails, for although his analysis showed a fair percentage of magnesium carbonate, he ignores it in his theoretical considerations. Speaking of the plant-containing nodules, he says that "their calcification was most probably due to the abundance of shells afterwards

accumulated in the soft mud and then decomposed, and now forming the shale overlying the coal." From the shells, even had they been completely decomposed and their carbonate percolated through to the plant beds below, could have arisen no source of the magnesium carbonate which must have been at hand.

Possible Source of the Magnesium.—We have mentioned above (p. 194) that there is evidence of marine conditions at once succeeding the deposition of the coal in which true coal balls are found, and the case described where they occur in the Gannister Seam (p. 188) seems very clear evidence that the sea water is of importance in their formation. As is well known, magnesium is largely found in a soluble form in nature, yet the formation of numerous coal balls with as much as 40 per cent. magnesium carbonate, and huge masses of dolomite, as at the Wirral Colliery, shows that the source must have been sufficient to supply large quantities while these structures were forming.

In the Sea Water.—The conditions under which the balls were formed, in large areas of undisturbed coal, negative the possibility of dolomite or magnesium springs. In fact, without further preamble, we may state that we look to the sea water itself as the source of both calcium and magnesium in a soluble form. That sea water was there, and in large quantities, we know from the presence of the many marine shells immediately above the coal; that it must have penetrated and completely saturated the coal-forming masses of plants is inevitable, from their soft pulpy condition. That sea water contains a certain percentage of calcium and magnesium sulphates in solution is well known. The analysis quoted is the average resulting from a large number, and is taken from the "Challenger" Reports (see DITTMAR ('84), p. 204).

Of 100 per cent. of the total salts :—

		Per cent.
Sodium chloride	formed . . .	77·758
Magnesium chloride	,, . . .	10·878
Magnesium sulphate	,, . . .	4·737
Calcium sulphate	,, . . .	3·600
Potassium sulphate	,, . . .	2·465
Magnesium bromide	,, . . .	0·217
Calcium carbonate	,, . . .	0·345
		100·000

Hence the supply of sulphates of magnesium and calcium in the sea water, which must have been continually renewed as they were deposited, seems entirely adequate for the source required in the formation of the coal balls. When comparing our view with that of BINNEY and others, it may be noted how extremely small is the percentage of calcium carbonate, notwithstanding all the "decomposing shells." It may be further noted that percolating water charged with calcium carbonate, as

such, seldom deposits it except in some crevice or open space, and that the coal balls were evidently formed in a bed in which the matrix was practically solid or saturated, the depth of sea water immediately above the coal (the tranquillity and fineness of the deposits as well as the nature of the shells show that it was considerable) rendering it impossible that there should be small cavities left in the mass of vegetation.

Let us now consider the possible chemical processes by which the decaying plants would have converted the calcium and magnesium sulphates into carbonates, and have themselves lost much of their carbon, which was replaced by the minerals in the process.

Reduction of Sulphates by Carbon.—So far as we are aware, the only experiments bearing at all on the subject are those of STOCKS (: 02), in whose paper we find the account of several very interesting and suggestive experiments. His analyses of the coal balls, however (quoted for reference in our Table II, Columns VI and VII), were of two nodules which had strikingly little magnesium carbonate in their composition, viz., less than 2 per cent., while the iron pyrites was present in larger amount than is general. Hence, when applied to the formation of coal balls in general, his views require a certain amount of modification.

MURRAY and RENARD in the "Challenger" Report ('91) and MURRAY and IRVINE in other papers ('89 and '91) describe the process of reduction of the sulphates in sea water by organic matter. STOCKS (: 02) made experiments on the reduction of mineral sulphates by the carbon in decomposing organic matter, resulting in the formation of mineral carbonates and sulphuretted hydrogen.

The general changes resulting from the process are somewhat crudely expressed in the following equations, R being an earthy metal :—

$$\begin{aligned}
&(1)\ RSO_4+2C = 2CO_2+RS.\\
&(2)\ RS+2CO_2+H_2O = H_2S+RCO_3.CO_2.\\
&(3)\ RS+RCO_3.CO_2+H_2O = 2RCO_3+H_2S.
\end{aligned}$$

In some of STOCKS' experiments (p. 55) he left a solution of calcium sulphate with ferric hydrate in suspension in a closed bottle with fresh and decayed wood and decayed fish. After a year he found that calcium carbonate had been formed, leaving little or no calcium sulphate, and that some of the wood had been impregnated and fossilised, though most of the vegetable tissues had entirely disappeared.

He represents the reactions as follows :—

$$\begin{aligned}
&\left\{\begin{aligned}&CaSO_4+2C = 2CO_2+CaS,\\ &CaS+CO_2+H_2O = CaCO_3+H_2S,\end{aligned}\right.\\
&\quad Fe(OH)_6+3H_2S = 2FeS+6H_2O+S,
\end{aligned}$$

with other minor reactions.

Thus he shows a possible way in which the calcium carbonate and the iron sulphide might have been deposited round the plant tissues which they served to preserve. It will be noticed that for the carbonate of lime the soluble sulphate is demanded.

We have shown throughout this paper that it is just in those beds in which we get the evidence of marine conditions above the coal, presupposing the presence of sea water, that we find the mineralised "coal balls" in the seam.

We may adapt the process suggested by the "Challenger" Reports and STOCKS' work, making the changes required to bring it into harmony with the facts our series of analyses have revealed. From them we see that the part played by iron pyrites is not so great as was supposed by STOCKS, and that it may even be almost absent, as in Analyses Nos. I, II, and IV in our Table I. Further, that magnesium carbonate commonly occurs in considerable quantity in the "coal balls," and may often be present with calcium carbonate in the proportions of dolomite,* or in the form of a mixture of dolomite and calcium carbonate.

We may represent the process of reduction and deposition of the sulphates very crudely as follows :—

$$CaSO_4 + MgSO_4 + 4C = 4CO_2 + CaS + MgS,$$
$$MgS + CaS + 4CO_2 + 2H_2O = 2H_2S + CaCO_3.CO_2 + MgCO_3.CO_2,$$
$$CaS + MgS + CaCO_3.CO_2 + MgCO_3.CO_2 + H_2O = 2CaCO_3.MgCO_3 + 2H_2S,$$

with minor reactions, and others resulting in the formation of the free carbonates of calcium or magnesium.†

As is well known, in any process by which calcium and magnesium crystallise out as carbonates together, there is a tendency for the simple carbonates to crystallise out independently, as well as for the formation of dolomite. Such variations, which the analyses show must have been very frequent, can only have depended on minute local conditions which it would be impossible now to determine. These variations must have been extremely local, as is seen from the differences exhibited between coal balls from a single small area, at Shore (see Table I).

* It will be realised that the smaller percentage by weight of $MgCO_3$ than of $CaCO_3$ in the analyses depends on the less molecular weight of the former compound. $CaCO_3.MgCO_3$ would give by analysis weights in the proportion of 100 : 84, *i.e.*, almost exactly the proportions seen in Analysis I of Table I.

† The necessary carbon would be provided by the decaying fragments of plants and animals in the coal mass. A side light, yielding a certain amount of confirmation to the above views, is thrown on the subject by a consideration of the relative amounts of carbon present in living and fossil wood. Estimating from the results of several analyses which were taken from single pieces of petrified wood from nodules, and from the specific gravities of the same, a comparison was made between the amount of carbon actually present in a piece of fresh wood and in a piece of well-preserved fossil wood (showing, it will be remembered, all the detail of cell structure). The result was found to be that the living wood contains roughly three times as much carbon as does the fossil wood. The deficit in the case of the fossil may reasonably be looked upon as having been used in the process of the reduction of the sulphates, as shown in the equations above.

Preservation of Delicate Tissues before Petrifaction.—We have already remarked on the beauty of the preservation of tissues which are extremely fragile and liable to destruction (see p. 172, and fig. 1). These structures clearly indicate that no theory of petrifaction would be complete which did not give at least some plausible explanation of the preservation of such minute and delicate tissues during the process of petrifaction, a process which, as STOCKS (:02) points out, and which everyone recognises, must have been very slow. The decaying mass of plant tissues, rich in bacteria, and decomposing into structureless coal, contained in itself only the seeds of decay. When dealing with the problem of coal, it is commonly assumed that the "peaty acids" of which so much is spoken played a considerable part. We must here point out that the coal-forming mass of vegetation, though undoubtedly rich in peaty acids, does not correspond to true peat in the sense in which we are accustomed to use the word; the plants preserved in the coal balls are not those of a peat bog, but are those of a crowded forest growth, with many kinds of plants, fragments of which have fallen upon the floor and been slowly accumulated.

Resistance of Tissues to Decay.—There are so few authentic experiments on the resisting power of plant tissues, that there are not sufficient data on which to base a broad generalisation. The experiment made by Professor LINDLEY still remains practically the only one which can be quoted in this connection (see LINDLEY and HUTTON, '37, vol. 3, p. 4). The results of the experiment on a large number (177 plant species) showed that of them but one-third left any trace after immersion in fresh water for a period of two years. The conclusions may be summarised as follows:—Leaves and bark of most dicotyledons were wholly decomposed, though Coniferæ and Cycads resisted fairly well; of monocotyledons, the Palms and Scitamineæ resisted well, but the sedges and grasses entirely perished; fungi and mosses, and all lower forms absolutely disappeared; ferns resisted well if gathered green, but their fructifications tended to decay.

LINDLEY gives no details of the type of preservation of the internal tissues, though he mentions in several cases that the skeletons alone were preserved. As those plants which remained recognisable after the immersion were chiefly those with thick cuticles and a large proportion of sclerised and hard tissues, it is reasonable to suppose that the most delicate cells had decayed.

The experiment was made with ordinary fresh water, which was renewed as it evaporated away, thus the plants were under less favourable conditions for their preservation than would be the remains in water saturated with peaty acids, or, as we will show below, in sea water.

Preservative Properties of Sea Water.—The descriptions given in the previous sections of this paper show that there are good grounds for believing that the plants petrified in coal balls were in a large mass of decaying vegetation, saturated with sea water and in the neighbourhood of the decaying bodies of mollusca. These condi-

tions we tried to reproduce in the laboratory, in order to ascertain whether they were favourable to the ordinary preservation of the tissues of plants.

Experiments with Plants in Sea Water.—The following arrangements were made :—At the bottom of a deep jar a layer of a couple of inches of peat was placed, on this pieces (in a fresh condition) of the following plants :—

Cycas riumimana (seed).
Cycas revoluta (leaf).
Marattia attenuata (sterile leaf and fertile leaf).
Dicksonia antarctica (sterile leaf and fertile leaf).
Polypodium, sp. (leaf, sterile and fertile).
Marchantia (thallus).

These were covered by a similar layer of three or four inches of peat; on them were placed a number of living and recently dead mussels and cockles and a handful of pounded shells. The whole was then filled up with fresh sea water, covered, and allowed to stand undisturbed.

After nearly ten months the jars were opened, and, except in the case of one in which a very large number of animals had been placed, were found to be entirely without smell, and the water looked quite clear. Of the animal bodies, not the slighest trace remained; the shells were quite clean and empty, and the water apparently pure. The plants, however, were in a wonderfully fresh condition, the leaves of all the plants, and even the *thallus of Marchantia*, were quite undecayed, and had retained most of their green colour. The only plant tissue which had decayed was that of the outer flesh of the integument of the cycad seed; this had split into several segments, opening away from each other, and revealing its inner face *in a decayed condition of soft pulp* which was distinctly odorous when exposed.

Sections were cut of the tissues of the other plants, and these showed that almost every cell was preserved *perfectly, as if fresh*, even the chlorophyll grains were green and distinct in the mesophyll. The phloem in some cases was somewhat destroyed, but in the fresher leaves it was perfect, with even the nuclei of the parenchyma cells unaltered. The cells of the liverwort thallus were equally well preserved. The sori of the ferns were less perfect, but were quite recognisably preserved.

The fresh green colour faded somewhat on exposure to the light, but the plants did not lose it till they were put in alcohol for section cutting.

A few of the freshest of these plants were then sealed in a small glass tube (5 inches $\times$ $1\frac{1}{2}$ inches) with some of the clear liquid from the experimental jars and a small quantity of air. This tube has been left exposed to the light and has been untouched ever since; the plants have still much of their green colour, as seen when they are held up against the light, and even the liverwort is still, apparently, well preserved. This is after a period of nearly two years, and in the comparatively unfavourable condition of exposure to light, and of enclosure in a very limited

quantity of preservative fluid.* When these results are compared with those obtained by LINDLEY with fresh water, it will be seen how immensely greater is the preservative power of sea water, even when a fruitful source of decay is supplied in the form of dead shell-fish. Reference to LINDLEY'S lists will show that of all the Lichenes, Hepaticæ, and Musci which he put in his tank at the beginning of the experiment, no trace remained after two years had elapsed; while in our experiment, after nearly two years, there is still the nearly perfect thallus, showing a tinge of green colour.

Hence, in the sea water saturating the plant masses, we find not only the supply of sulphates which were slowly reduced by some of the decaying plants (some parts of the plants, as we saw in the fleshy coat of the cycas seed, would decay rapidly, others would yield after a long period), but the medium which preserved the plant tissues from decay in the long interval before the fossilisation was completed. We must remember that however rapid, geologically speaking, was the accumulation of a seam of coal and the roof over it, yet it must have been measured in tens of years at the very least, and that therefore this preservative property of the sea water must have played a very important part in the early stages of the petrifaction of plants.

Summary of Section IV.

In this section we have given the detailed chemical analyses of the "coal balls" and roof nodules, and noted their bearing on the formation of the structures: pointed out the marine roof lying over the coal and the importance of its position as indicating the presence of sea water and the consequent saturation of the accumulated plant remains: noted the presence of so large a proportion of magnesium carbonate in the coal balls as to necessitate a source of soluble magnesium salts: indicated that in sea water there are the necessary calcium and magnesium sulphates which are reducible by organic carbon: proved the important preservative properties of sea water for plant tissues: and in short indicated that the sea water played the principal part in the process of preserving and petrifying the plant remains now found in coal balls.

Before going on to consider the general aspect of the facts contained in the foregoing sections, and the picture they yield of the physiography of some of the areas in the Coal Measures, we will turn to the comparison of the floras which are preserved in the coal balls, shale impressions and roof nodules of the beds under discussion. From this comparison, facts of importance are to be gleaned, which will be used in the argument of the sixth section.

* No further change has yet taken place in these plants, although they have been immersed for three years.—D. M. S. W., July 6, 1908.

Section V.

Comparison of Floras represented in the "Coal Balls," "Roof Nodules," and Shales of the Lower Coal Measures.

The "Goniatite nodules," which occur in the roof above the coals where "coal balls" are found, generally contain animal fossils alone; there are, however, numerous exceptions, in which plant stems or petioles lie in the midst of the masses of shell *débris* and fine calcareous mud which compose them. Usually but one plant occurs in a nodule, and it is generally in the form of stem or sturdy petiole in which they are found, rather than delicate leaves or sporangia. In these plants, the tissue is sometimes exquisitely preserved locally, but in most cases the tissues are suddenly absent or torn in places, as though parts had suffered some accident out of the course of simple decay, which would tend to destroy the tissues more systematically.

"Roof Nodule" Plants drifted.—Their position also, in the midst of marine shells, and entirely isolated from each other, proves them to be plants which have drifted out to sea, possibly for some considerable distance, during which they have undergone various vicissitudes, but have had their delicate tissues preserved by the sea water (see p. 201), before they finally sank in a waterlogged condition upon the sea bottom amid the Goniatites and other shells. That they were not formed directly at the estuary mouth, or on a shore line, is shown by the very delicate and even bedding of the nodules in which they lie and by the absence of all quartz grains or large *débris* in them, and the relatively small quantity of even the finest mud.

Represent a different Flora from that of the Coal Balls.—That the plants petrified in the roof nodules represent a flora of a different character from that of the "coal ball" plants has been remarked on several occasions (SCOTT, March, :06, p. 1, and October, :06, p. 148, STOPES, May, :06, p. 18), and, as SCOTT points out, has in several respects a Permian facies, although undoubtedly being of Lower Coal Measure age.

The number of actual species which are confined to either the "roof nodules" or the "coal balls" is not so great, as will be seen from the following lists, but in addition to them are found plants which are common in the roof and rare in the seam, or which abound in the seam and are very scarce in the roof.

Owing to the relative scarcity of roof nodules containing plants, and to the fact that a given roof nodule will contain but one species, while a "coal ball" may contain 20, the number of plants which are recorded from the roof is relatively small as compared with those from the seam.

FOSSIL Plants Recorded from "Roof Nodules."

Calamites, sp.
**Lepidodendron Harcourtii*, WITHAM.
Lepidodendron Hickii, WATSON.
Lepidostrobus Oldhamius, WILL.

Sigillaria elegans, BRONGN.
Sigillariopsis sulcata, SCOTT.
**Tubicaulis Sutcliffii*, STOPES.
**Zygopteris diupsilon*, WILL.
,, *grayi*, WILL.
Psaronius Renaultii, WILL.
Medullosa anglica, SCOTT.
**Sutcliffia insignis*, SCOTT.
* ,, *Williamsoni* (SEWARD).
Myeloxylon, sp. nov. (?)
**Poroxylon Sutcliffii*, SCOTT, M.S.
**Cycadoxylon robustum* (SEWARD).
**Trigonocarpus Oliveri*, SCOTT and MASLEN.
Cordaites, sp.

Those marked * have not been recorded from the seam, so far as we are aware.

The most remarkable point about this list is the absence of any part of the plant *Lyginodendron*; so far as we can ascertain, no fragment of this plant has been found in a roof nodule, although it is, with the exception of the ubiquitous Stigmarian rootlet, the very commonest of those found in such abundance in the seam. It is also noticeable that all species of *Lepidodendron* except *L. Harcourtii* and one specimen of *L. Hickii* are absent, that *Sphenophyllum* is entirely absent, and that most of the species included under the genus *Rachiopteris* WILLIAMSON are quite unrepresented, although very common in the coal balls.

The geological characters and position of the two types of nodules clearly prove that the difference in age between the roof beds and the coal itself must be extremely small, and can in no degree be held responsible for this difference in the floras. While pointing out (p. 204 *antea*) that the plants in the roof nodules must have drifted a considerable distance, no conclusion was drawn as to the source of these plants. The marked difference in the characteristic species of the two floras shows that the roof nodule plants are not simply drifted samples of those of the seam, but represent an association of plants which grew apart. From the study of their internal anatomy, the conclusion has been drawn that the typical "coal ball" plants inhabited a swampy district and grew with their roots submerged and their branches exposed. It is noticeable that the roots of the principal plants, *Calamites*, *Lepidodendron*, *Sigillaria*, and *Lyginodendron* had lacunar cortices, while the very xerophytic type of most of the leaves in the coal balls suggests that the swamp water was either almost saturated with organic acids or was salt (*cf.* SEWARD and HILL (:00)). The structure of the plants in the roof nodules, on the other hand, is much more nearly comparable with that of plants growing on dry ground. The natural conclusion is that the roof flora is formed from plants growing on some higher ground than the coal swamps, fragments

LIST of Fossil Plants from the Coal Balls of Lancashire and Cheshire.*

Plant.	Principal locality.
Calamites communis, BINNEY	Widely spread
,, sp. (type undescribed)	Oldham
,, sp.	
Calamostachys Binneyana, SCHIMP.	,, Shore, Dulesgate, etc.
,, *Casheana*, WILL.	Oldham
,, *Oldhamia*, HICK	,,
,, sp.	Shore.
Calamite roots (Astromyelon and Myriophylloides)	Dulesgate and elsewhere
Palæostachya vera, SEWARD	Oldham
Sphenophyllum plurifoliatum, WILL. and SCOTT	Widely spread
,, *Dawsoni*, WILL.	Oldham, Shore, Dulesgate, etc.
,, *fertile*, SCOTT	Shore
Lepidodendron fuliginosum, WILL.	Widely spread
,, *Hickii*, WATSON	Hough Hill, Dulesgate
,, *macrophyllum*, WILL.	Oldham, Shore, Stalybridge
,, *parvulum*, WILL.	Oldham
,, *vasculare*, BINNEY	Widely spread
Lepidophloios sp. nov., WATSON	Shore, plentiful there, not elsewhere
Lepidostrobus oldhamius, WILL.	Oldham, Shore, etc., widely spread
,, *foliaceus*, MASLEN	Dulesgate
Lepidocarpon Lomaxi, SCOTT	Oldham, Dulesgate, etc.
,, sp. nov.	Dulesgate, Hough Hill
Spencerites insignis, WILL.	Dulesgate
Miadesmia membranacea, BERT.	,, Hough Hill
Bothrodendron mundum, WILL.	Oldham, Hough Hill, etc.
Sigillaria tessellata, BRONGNT.	Oldham
,, *elegans*, BRONGNT.	Shore, Oldham
,, *scutellata*, BRONGNT.	Dulesgate
,, sp.	Widely spread
Stigmaria ficoides, BRONGNT.	Everywhere
Sigillariopsis sulcata, SCOTT	Shore, Dulesgate
Psaronius Renaultii, WILL.	Oldham, Dulesgate
Hymenophyllites sp., KIDSTON	Oldham
Rachiopteris cylindrica, WILL.	Hough Hill
,, *rotundata*, CORDA	Oldham, Hough Hill, Shore, Dulesgate
,, *oblonga*, WILL.	Oldham
Botryopteris hirsuta, WILL.	,, Shore, Hough Hill
,, *tridentata*, FELIX (petiole of *B. hirsuta*)	,, ,, ,, etc.
,, *ramosa*, WILL.	,, Dulesgate, Stalybridge
,, *robusta*, WILL.	,, and nearly everywhere else
Zygopteris bibractensis, RENAULT	Dulesgate, Shore, Hough Hill, etc.
,, *Grayi*, WILL.	Oldham
,, *Lacatti*, RENAULT	Dulesgate, Shore, Hough Hill, Oldham
Cyathotrachus altus, WATSON	Shore, Dulesgate
Pteridotheca Williamsoni, SCOTT	,, ,,
Stauropteris Oldhamia, BINNEY	Oldham, Shore, Hough Hill, etc.
Heterangium Greivii ? WILL.	Dulesgate
,, sp.	,,
,, *tiliaoides*, WILL.	Laneshaw Bridge
Lyginodendron oldhamium, BINNEY	Universal
,, (roots) *Kaloxylon Hookeri*, WILL.	Widely spread
,, (petioles) *Rachiopteris aspera*, WILL.	,,

* Halifax has been excluded from this list because it is in Yorkshire, and in dealing with the impressions we confine ourselves to Lancashire and Cheshire for obvious reasons.

LIST of Fossil Plants from the Coal Balls of Lancashire and Cheshire—*continued.*

Plant.	Principal locality.
Lagenostoma Lomaxi, WILL.	Oldham, Hough Hill, Dulesgate, Shore
,, *ovoides*, WILL.	Dulesgate, Shore, etc.
Telangium Scotti, BENSON	Shore, Dulesgate, etc.
Conostoma oblonga, WILL.	Oldham, Dulesgate, Shore
Physostoma elegans, WILL.	Dulesgate, Shore, Oldham, and Bacup
Medullosa Anglica, SCOTT	Hough Hill, Shore, Oldham
Myeloxylon	,, ,, ,,
Trigonocarpus Parkinsoni, BRONGNT.	,, Oldham, Dulesgate, Shore
Cordaites, sp. (stem)	Shore, Dulesgate
,, sp. (leaves)	Shore
,, *Amyelon radicans*, WILL.	Dulesgate, Shore, Bacup
Cardiocarpon compressum, WILL.	Oldham, Shore, Dulesgate
,, *Butterworthi*, WILL.	Oldham
Mazocarpon, SCOTT	Shore, Dulesgate, Hough Hill
Sporocarpon asteroides, WILL.	Dulesgate
,, *elegans*, WILL.	,,
Traquairia, sp.	,,
Zygosporites brevipes, WILL.	
,, *oblonga*, WILL.	
,, *longipes*, WILL.	

From this list one or two species have been omitted, which have been found only in Halifax and there fore do not come within its bounds.

of which had been brought down in streams or rivers, and carried some distance out to sea. These plants are therefore to be considered as more truly characteristic of the period than those which inhabited such a very special region as the swamps on the seashore which have bequeathed to us the coal.

Comparison with the Flora in Shales.—In this connection it is interesting to compare the plant impressions from the shales of the Lower Coal Measures. Apart from those found in beds distinct from the coal seams, many plant impressions have been recognised from the roofs of seams, and it has hitherto been assumed that the latter represent the plants which formed the coal.

A considerable list of species found in this form as impressions from the Lower Coal Measures and Millstone Grit follows :—

LIST of Plant Impressions from the Lower Coal Measures and Millstone Grit of Lancashire and Cheshire.

Plant.	Horizon.	Principal Locality.
Calamites ramosus, ARTIS	Higher Early Banks Mine	Hough Hill
,, (*Calamitina*) *undulatus*, STERNB.	Lower Coal Measures	Eagley Shore, Bolton
Annularia radiata, BRONGNT.	Higher Early Banks Mine	Hough Hill
	Sandrock Mine	Marcroft

LIST of Plant Impressions—*continued.*

Plant.	Horizon.	Principal locality.
Pinnularia capillacea, LIND. and HUTT.	Between Gannister and Upper Foot Mine	Bacup
**Calamcoladus equisetiformis*, SCHL.	Lower Coal Measures	Poynton, Cheshire
Calamostachys, sp.	Higher Early Banks Mine	Hough Hill
	Sandrock Mine	Marcroft
Paracalamostachys Williamsoniana, WEISS.	Brooksbottom Coal	Ewood Bridge
**Palæostachya*, sp.	Sandrock Mine	Marcroft
Lepidodendron aculeatum, STUR.	Lower Foot Mine	Clough, near Shore and Bacup
" *lycopodoides*	Over First Coal	Stalybridge
" "	Sandrock Mine	Marcroft
" *obovatum*, STERNB.	Gannister	Crompton Fold (very common).
" *ophiurus*, BRONGNT.	"	Bacup
Lepidophyllum majus, BRONGNT.	"	"
* " *lanceolatum*, LIND. and HUTT.	Sandrock Mine	Marcroft
**Lepidophloios acerosus*, LIND. and HUTT.	" "	"
" "	Second Grit	Deene Brook
" "	Gannister	Bacup
* " *laricinus*, STERNB.	Over Early Banks Mine	Hough Hill
	Second Grit	Deene Brook
Halonia	Over Upper Foot Mine	Stalybridge, Ogden
Lepidostrobus, sp.	Gannister and others	Oldham, etc.
Bothrodendron minutifolium, BOULAY, sp.	Lower Coal Measures	North of Bolton
Sigillaria elegans, STERNB.	Gannister	Deerpley
" "	Upper Mountain Mine	Dulesgate
" *discophora*, KÖNIG	Gannister	Old Meadows
" *mamillaris*, BRONGNT.	" Roof	Bacup
" *tessellata*, BRONGNT. {	"	Crompton
	Woodhead Hill Rock	Bacup
Stigmaria ficoides, BRONGNT.	Lower Mountain Mine, etc.	Darwen, etc.
Mariopteris muricata, SCHL.	Second Grit	Deene Brook
(Very widely spread)	Sandrock Mine	Marcroft
" "	Higher Early Banks Mine	Hough Hill
" "	Over Gannister, etc.	Bacup, etc.
Alethopteris lonchitica, SCHL.	All horizons	Widely scattered
**Crossotheca Hoeninghausi*, BRONGNT.	? Gannister	Near Moorcock, Ogden
Neuropteris heterophylla, BRONGNT.	Higher Early Banks Mine	Hough Hill
" "	Lower Coal Measures	North Bolton
Sphenopteris obtusiloba, BRONGNT.	" " "	" "
" *Schillingsii*, ANDRAE	Upper Mount Mine	Bacup
" sp.	Gannister	"
Megaphyton, sp.	"	Old Meadows, Bacup
Cordaites borassifolius, STERNB.	Second Grit	Near Bacup
* " sp. (branch)	Roof of Mount Four-Feet Mine	Deerpley
" " (leaves)	Upper Foot Mine	Shore, etc.
Leaves common on several horizons.		
Trigonocarpus Parkinsoni, BRONGNT.	Above Mountain Mine	Fox Clough, Colne
Artisia (*Sternbergia*) *approximata*, BRONGNT.	Below Gannister	Bacup
" " *transversa*, ARTIS	" "	"
**Antholithus Pitcairnii*, LIND. and HUTT.	Above Mount Four-Feet	Fox Clough, Colne
**Samaropsis*	Sandrock Mine	Marcroft

Many of these plants are taken from KIDSTON'S Lists (see KIDSTON '92 and '94). Those marked * are recorded from the horizons given for the first time, so far as we are aware.

The points to be specially noticed on comparing the above list with that given of the plants of the coal balls are :—

(1) The commonest "fern" among the impressions is *Alethopteris lonchitica*, BRONGNT.; this is the foliage of one of the Medullosæ, which are among the rarest plants in the coal balls. The next commonest "fern" impression is *Mariopteris muricata*, an impression which has not yet been correlated with any form in the coal balls.

(2) *Cordaites* leaves are common as impressions, and occur in more than one horizon, but in the coal balls they are very rare, though the stems are found commonly in the roof nodules.

(3) No impressions of *Sphenophyllum* have yet been found, although they are common enough in the coal balls; further, the plant has not been recorded from the roof.

(4) *Crossotheca Hoeninghausi* (*Lyginodendron*) is exceedingly rare in the form of impressions, having only been found in two ironstone nodules from a single locality, and although it is the commonest plant in the coal balls, no portions of it have yet been found in the roof.

Flora in Shales distinct from that in Seam.—Hence it seems probable that the flora we know as impressions is not the same as that in the coal balls, but corresponds more closely to the series of plants which are typical of the roof nodules. It is therefore seen to be an insecure chain of argument to deduce the nature of the plants forming the coal from those found in the roof unless there is some definite indication that they coincide.

The evidence given in the earlier portions of this paper shows that the coal balls, having been formed in the coal, contain a fair sample of the plants forming it; we have now seen that these plants represent a flora distinct from that in the shales above the coals. The plants in the shales have undoubtedly drifted, probably from a land area where the flora was similar to that represented by the plants in the roof nodules. It may be remarked that this furnishes additional support for the theory of the origin of the coal balls in the seams in which they now occur. Did they represent a drifted flora they would have more in common with the drifted floras of the shales and roof nodules. Further, this comparison yields strong support to the view that the coals themselves have not drifted, but have collected where they grew; a view which is in harmony with the fact that clays or "gannister" floors contain nothing but rootlets and underlie the seams. Our conclusion is that these coals were formed *in situ*, and that in them the "coal ball" concretions were slowly aggregated without any serious disturbance. Trifling drifting, due to local currents or streams is, of course, not to be denied, but in the main the coals represent forests which grew where their remains now lie. We here touch the larger question of coal formation, as well as that of the coal balls themselves, because the facts quoted seem to afford practical proof of the *in situ* theory of the formation of the coal. Nevertheless, the day is past

when geologists would apply any one theory to all the coal seams, and our views refer only to those of which we have special knowledge, viz., those containing "coal balls."

SECTION VI.

General Conclusions.

From the data set forth in the preceding sections it is possible to form a mental picture of the area in which the coals yielding "coal balls" were laid down, and to follow the series of events which resulted in their formation. In such a picture, an attempt is made to summarise, in a graphic form, the general conclusions to which we have come :—

Groves of large trees with smaller herbs and ferns finding place between and around their stems grew in the flat swampy levels between the higher ground and the sea. The water round their roots was brackish or salt, as is the water of the mangrove swamps to-day, and into its quiet pools and shallows twigs and branches, stems, leaves, and fruits fell or were blown. These fragments sank into the mass of *débris* already saturated and were there shut out from the atmosphere and preserved by the salt water in which they lay immersed. Parts of the plants decayed and thus liberated the organic carbon, which began its slow task of reducing the sulphates and depositing them as insoluble carbonates. This process continued long without the entry of impurities or the deposition of anything but plant remains, and the rootlets of the living plants wandered among the dead ones, finding their way even through the heart of their stems or seeds.

All the time the land was slowly sinking, and when several feet of *débris* had accumulated the level sank more abruptly till the plants were well submerged and the place where the forest trees had lived was covered by the waters of an arm of the sea. Over them was deposited fine mud, with the shells

References.

Sigillarias, Lepidodendrons, and Calamites, see lists of plants given on p. 206.

Anatomy of plants suggests xerophytic swamp conditions.

Seen in coal balls in section, list on p. 206.

Practically pure plant *débris*, as seen in the character of the coal, which is free from quartz, mud, etc.

See experiment, p. 203.

Compare cycad seed coat, p. 202.

See formulæ on p. 200.

Guaranteed by thickness and purity of coal.

Frequently seen in microscopic sections, where the rootlets penetrate other tissues of all kinds, most of which are not otherwise destroyed.

This is in the case of the Upper Foot Mine, where the resulting coal is about 1 foot thick, see p. 174.

The marine shells in roof prove this, see p. 167.

Evidence drawn from the character and distribution of the coal seams indicates that the shore line was very irregular, with long inlets stretching inland.

of *Goniatites* and *Aviculopecten* which lived and died in the waters. The plant masses below were continually withdrawing the sulphates of lime and magnesium from the sea water and depositing them as carbonates round the many centres started among the fragments of plants. The supply of salts was inexhaustible, for new water mingled continually with the old and brought fresh sources of mineral to petrify the plants. Thus in the heart of the masses of coal were formed large and small concretions of carbonate, some regular as balls and very large, others minute and uniting together to form wisps or sheets of stone lying in the coal.

The stony masses hardened, and as the weight above gradually pressed down the soft plants which would ultimately form the coal, they withstood the crushing uninjured, the delicate tissues embedded along with scraps of young plants which had but begun life, and were at once preserved alike from further growth and from decay.

In the sea above, the currents carried fragments of plants from the neighbouring land, brought by the streams from the higher ground. These sank in the muddy floor and were gradually crushed by the silt collecting above them, till they were flattened as impressions in the beds which afterwards formed shales. Others, sinking upon the floor of the sea where the many decaying animals liberated so much carbon that the sulphates in the water were converted into carbonates, were slowly petrified—but not before the vicissitudes of their journey had partly destroyed and torn them, yet those of their tissues which escaped these ravages were so well preserved by the sea water that their every cell was petrified by the deposited carbonates, which formed

References.

Fig. 16, Plate 19.

See concretionary nature illustrated in fig. 13, also p. 199.

See illustrations in Plates 18 and 19.

Cf. Wirral and Accrington beds, p. 176.

See p. 174, and fig. 4, Plate 17.

See fig. 1, Plate 17, also p. 172.

The "roof nodules" described on p. 173.

See conclusions on p. 204.

The isolated plants in the "roof nodules" are associated with innumerable shells.

The curiously fragmentary nature of the inner tissues in "roof nodules" is suggestive of this.

Some examples of unsurpassable perfection of preservation of delicate tissue are found in stems otherwise much torn and fragmentary.

References.

concretions round them and enclosed at the same time so many shells.

These drifted plants, whether their fate was to be enclosed in the preserving nodules or to be crushed into the shales, had principally come from regions different from those which had produced the half-formed coal now lying immediately below them.

See p. 209.

Slowly they too were covered by the fine deposits which collected gently over them, until the sea bottom rose again to form a new land. All this time the plants were preserved in the coal balls without disturbance or hurt, and although the coal-forming *dêbris* had been pressed down into coal which was now but a foot in thickness, they remained uncrushed in their original form.

Geological evidence from character of beds.

See p. 172 in particular, but practically the whole of Section II illustrates this, see Summary on p. 174.

See fig. 1, Plate 17.

This has happened with slight variations many times in the course of the history of the world ; but only where the land rose and sank gently and the plants were covered as they fell in a still inlet of the sea. Where the plants were hurried down to sea and collected together swiftly and then covered by a sandy or estuarine deposit forming rapidly, there no "coal balls" are found.

See Section III and Summary on p. 191.

Compare the oolitic coal at Brora, Sutherland, which contains no coal balls, but has a roof of coarse sandy shale with marine shells, Ammonites, Trigonia, etc.

Thus, the "coal balls" in the coal are the relics of a forest which grew quietly in a swamp in the place where they are now found, while the plants in the shales and in the roof nodules above had drifted out to sea from other districts and bear in the character of their structures the impress of the different type of land on which they lived.

In conclusion, we may state the main theses of our paper in a few words, thus :—(*a*) The coal balls were formed in the position in which they are now found (and probably also the coal itself was likewise formed *in situ*) ; (*b*) the sea water was fundamentally important during the coal ball formation in acting both as a temporary preservative and as the source of the calcium and magnesium carbonates required for

petrifaction; (*c*) the plants in the roof nodules and shale impressions above the seam represent a different flora from that found in the coal.

ACKNOWLEDGMENT.

This work, covering as it does so wide a field, has only been possible owing to the helpful kindness of a large number of friends and fellow workers, as well as the ready courtesy and consideration yielded by mine owners and others on whom we had no claim. To all we express our hearty gratitude. The names of some who have rendered conspicuous service have been mentioned already in the text, but we would here renew our thanks to all the following, as well as many whose names are not specially mentioned :—J. BARNES, Esq., of Salford, who did a large number of chemical analyses; Professor W. BOYD DAWKINS, F.R.S., of Manchester; F. H. GRAVELY, Esq., B.Sc., of Manchester, who took several photographs of blocks of coal balls; W. S. GRESLEY, Esq., F.G.S., of Derby, who lent the specimen figured on Plate 17, fig. 5, and supplied information about Iowa; J. HARGREAVES, Esq., of Stalybridge, who gave us facilities for excavating on his land; Dr. W. E. HOYLE, Director of Manchester Museum, for the use of specimens required for our work; R. KIDSTON, Esq., F.R.S., for identification of impressions and other help; ILLINGWORTH LAW, Esq., of Bacup, for special help in his mine; JAMES LOMAX, of Bolton, for much information, many specimens and sections, and some of the photographs in the plates; G. MACALPINE, Esq., of Accrington, for facilities in his mine and very useful specimens; Professor F. W. OLIVER, F.R.S., of London; J. PLATT, Esq., of Neston, for facilities and specimens from the Wirral Colliery; the DIRECTORS and many of the Staff of the GEOLOGICAL SURVEYS of England and of Scotland; Dr. TIETZ, Director of the Austrian Geological Survey; Professor WEISS, F.L.S., of Manchester, in whose department every facility and help has been afforded; and finally to the ROYAL SOCIETY GOVERNMENT GRANT COMMITTEE, by whose aid most of the expenses connected with the work have been defrayed.

Many of the specimens figured and mentioned in the text, as well as others we have obtained, have been deposited in the Manchester Museum, and will be available there for reference.

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DESCRIPTION OF PLATES.

Photographs 3, 5, 7, 8, 9, 10, 11, 12, 13, and 14, by Mr. Gravely, Photographs 4, 19, and 20 by Mr. Lomax.

PLATE 17.

Phot. 1.—Longitudinal section of the growing point of root of *Lyginodendron oldhamium*, which shows the perfect preservation of the most delicate growing cells. From a "coal ball" from Dulesgate, Slide No. R646 in the Manchester Museum Collection. × diameters. (See p. 172.)

Phot. 2.—Small block of coal showing enclosed "coal balls" cut across and washed with acid to expose structure. The coal layers, C, are seen to bend round the coal balls, particularly round B′. (NOTE.—The streak in the photo bending in the direction opposite to that of the lamination is caused by the cutting disc.) (See p. 174.)

Phot. 3.—A block from a large "coal ball" showing a fault, which has broken the stem S, and shifted the halves along the line of the fault *f-f*. Manchester Museum, No. L. 7175. × 1. (See p. 174.)

Phot. 4.—View taken in the mine at Shore, showing the working face and exposing part of the huge two-ton "coal-ball" mass. S, shales of roof. R, large goniatite nodule in roof above the coal. C, coal. M, part of the huge coal ball mass, which fills the whole corner of the photograph and is seen *to double the thickness of the seam* and thus raise the position of roof shales lying directly above it. F, floor below coal. Below the huge mass the floor is considerably depressed. (See p. 174.)

Phot. 5.—Block from coal of Iowa, U.S.A., containing carbonate mass with plant fragments. Illustrating the complete similarity in form between this and typical "coal ball" formation as illustrated in Phot. 11. Slightly larger than natural size. Specimen belonging to Mr. Gresley, of Derby. (See p. 191.)

PLATE 18.

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Phot. 7.—Block of coal enclosing numerous small "coal balls" from typical Lower Coal Measure seam. Natural size. Manchester Museum, No. L. 7174. (See p. 177.)

Phot. 8.—Block from the Wirral Colliery, showing the rounded form of the dolomite masses in the coal. To be compared with Phot. 13, of true "coal balls" of small size. Slightly larger than natural size. From the specimen in Jermyn Street Museum. (See p. 177.)

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Phot. 13.—Section of *Stigmaria* from a Lower Coal Measure "coal ball," showing concretionary form of the carbonates forming between the woody cylinder and the outer cortex *c*. × about $1\frac{1}{2}$. Manchester Museum.

Phot. 14.—Section showing plant tissues preserved in carbonates from Great Harwood Mine. (See p. 176.) × 20 approx. Similar specimen in Manchester Museum, No. L. 7181.

Phot. 15.—Part of the dolomite mass from the Wirral coal seam enlarged to show concretionary structure of the dolomite, with small streaks of coal between. × 9. Section belonging to the Jermyn Street Museum. (See p. 177.)

Phot. 16.—Roof nodule, broken open, showing a band of large Goniatites. Slightly reduced. (See p. 180.)

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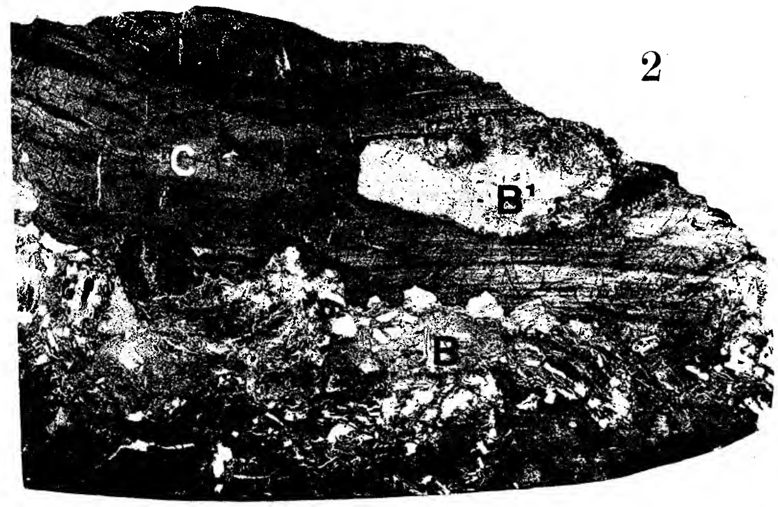

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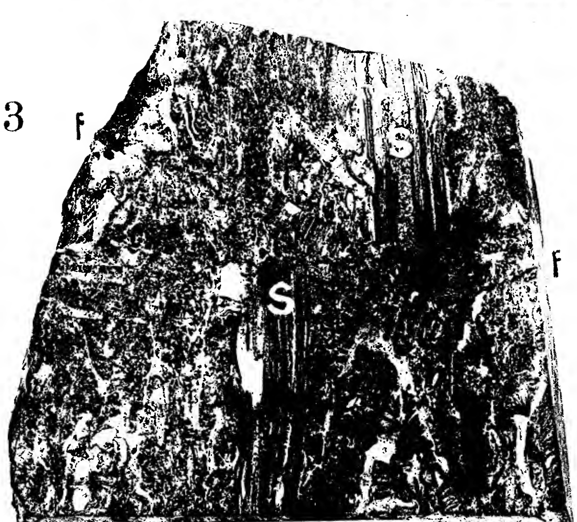

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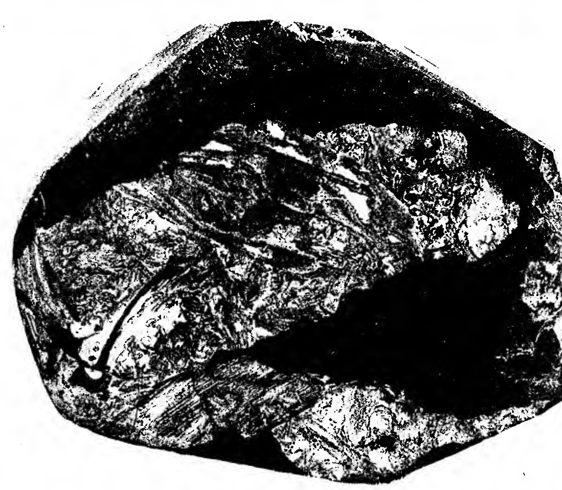

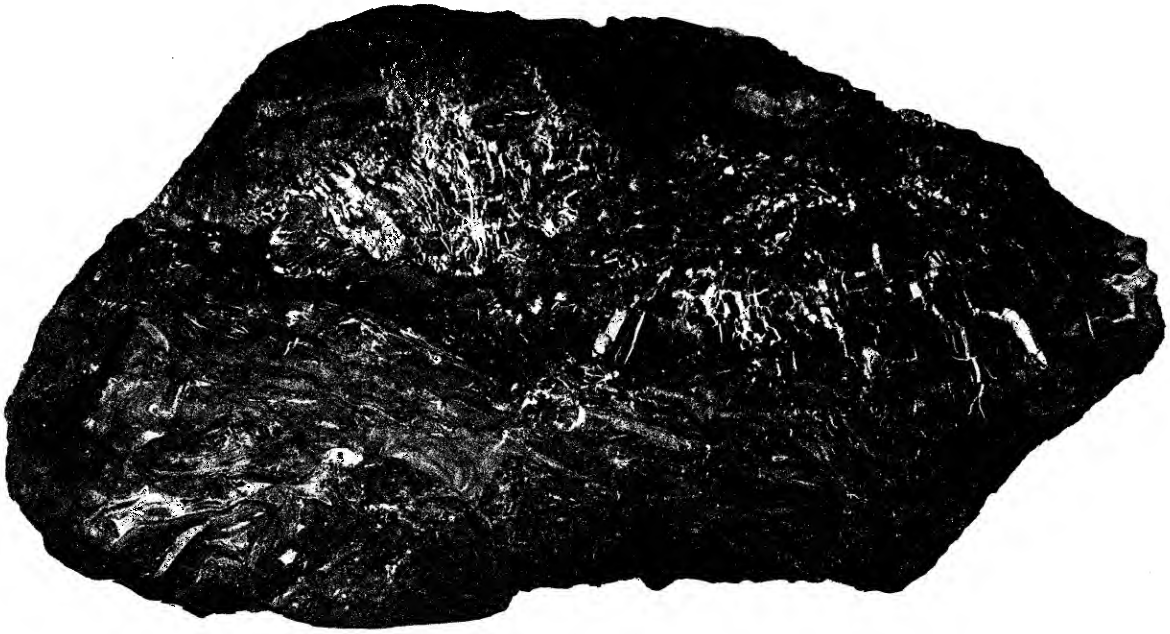

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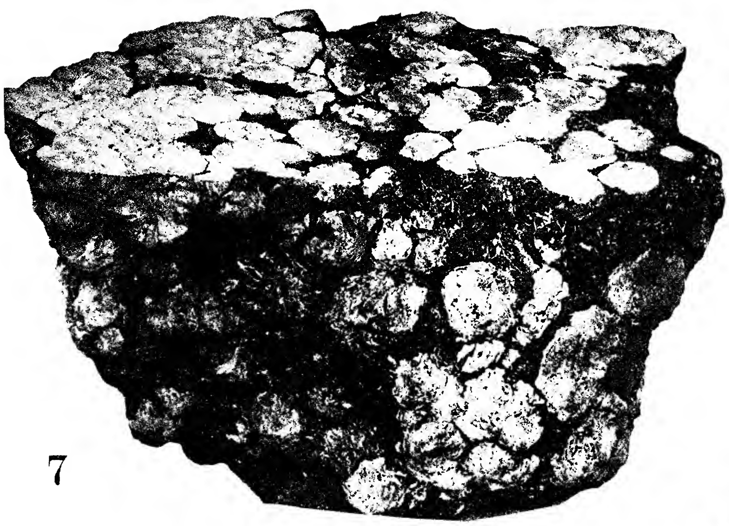

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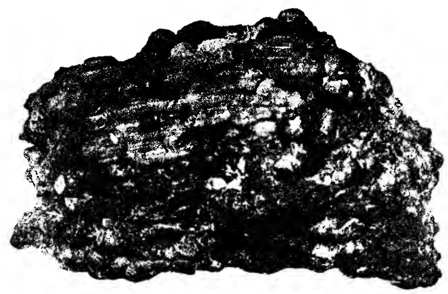

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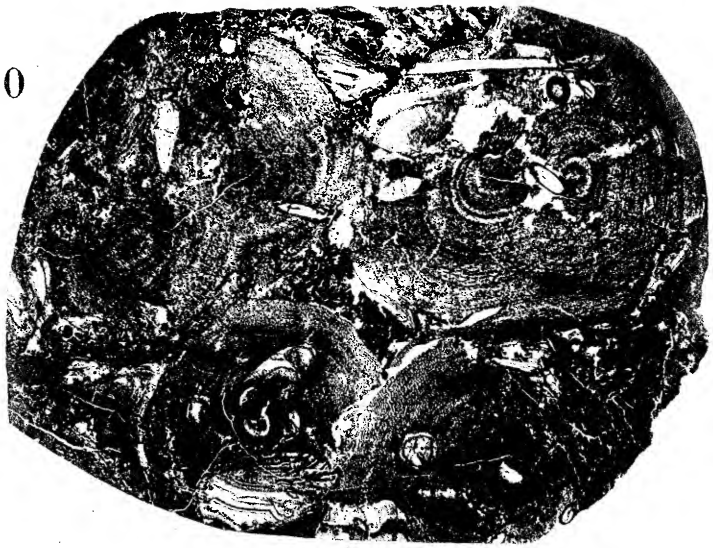

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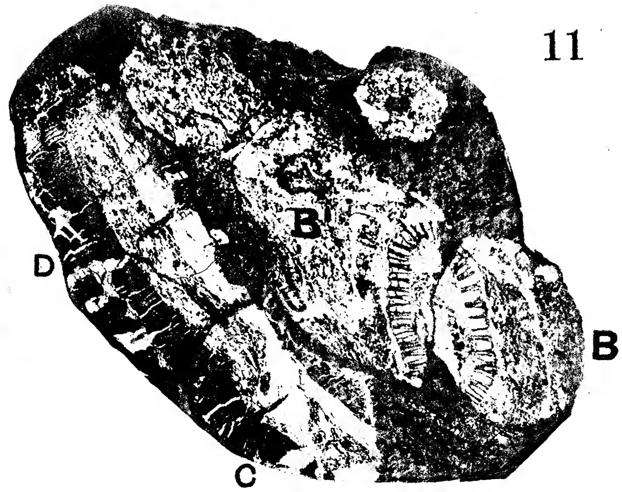

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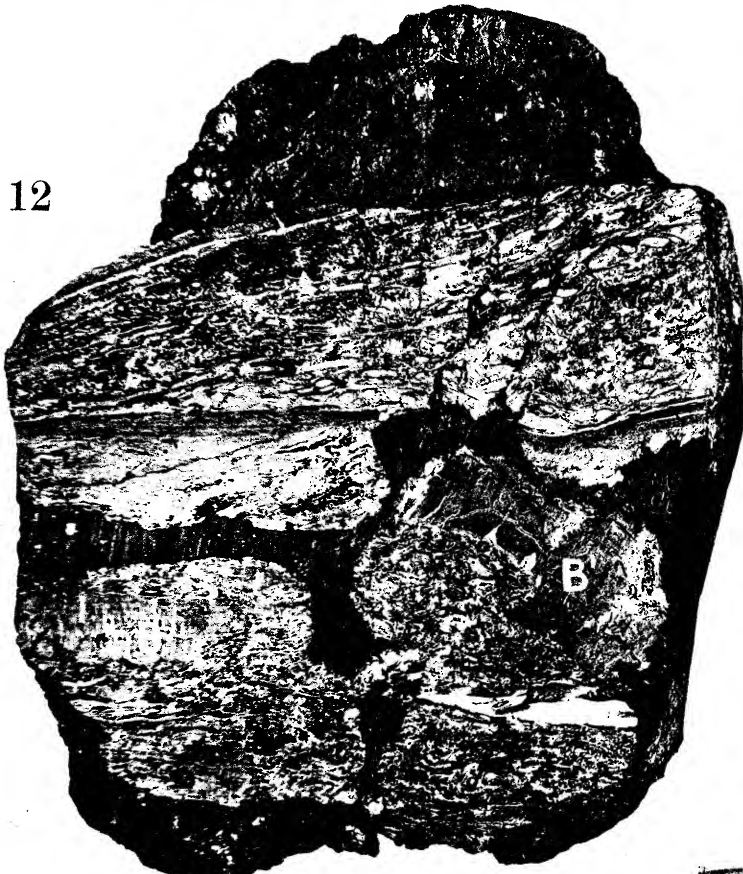

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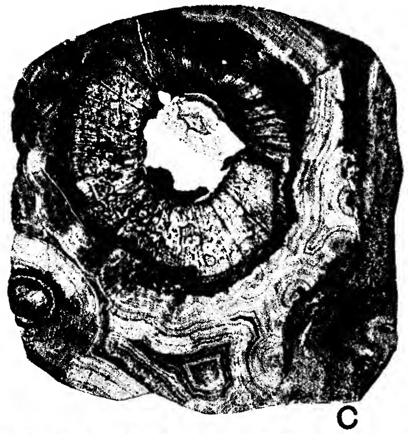

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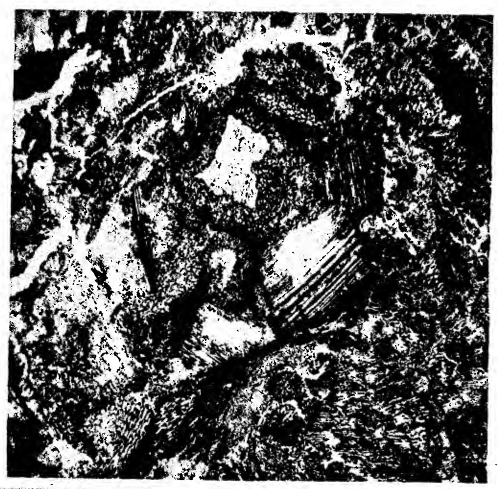

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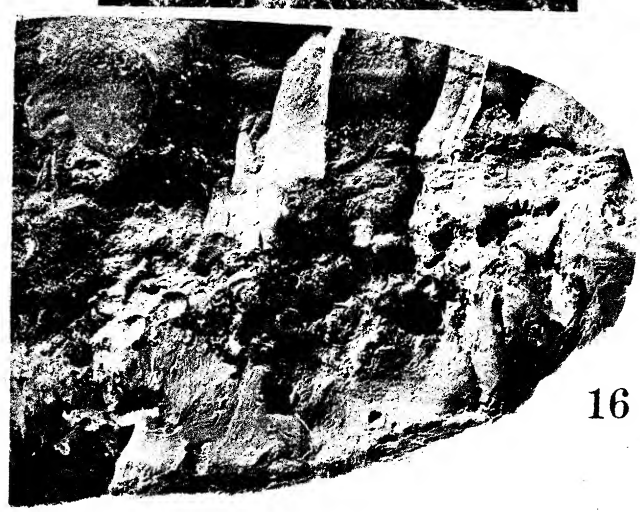

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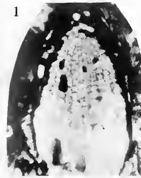

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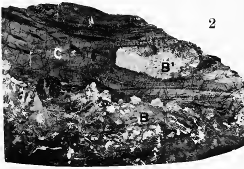

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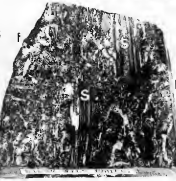

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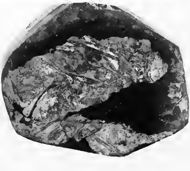

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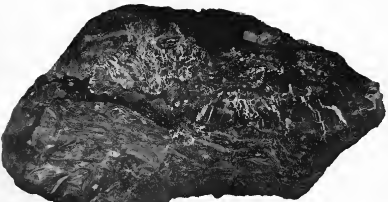

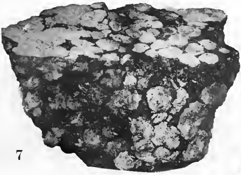

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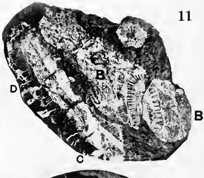

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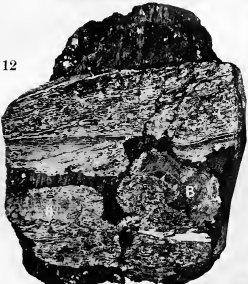

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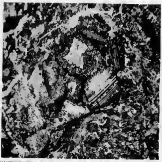

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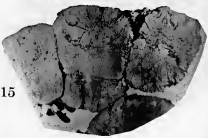

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